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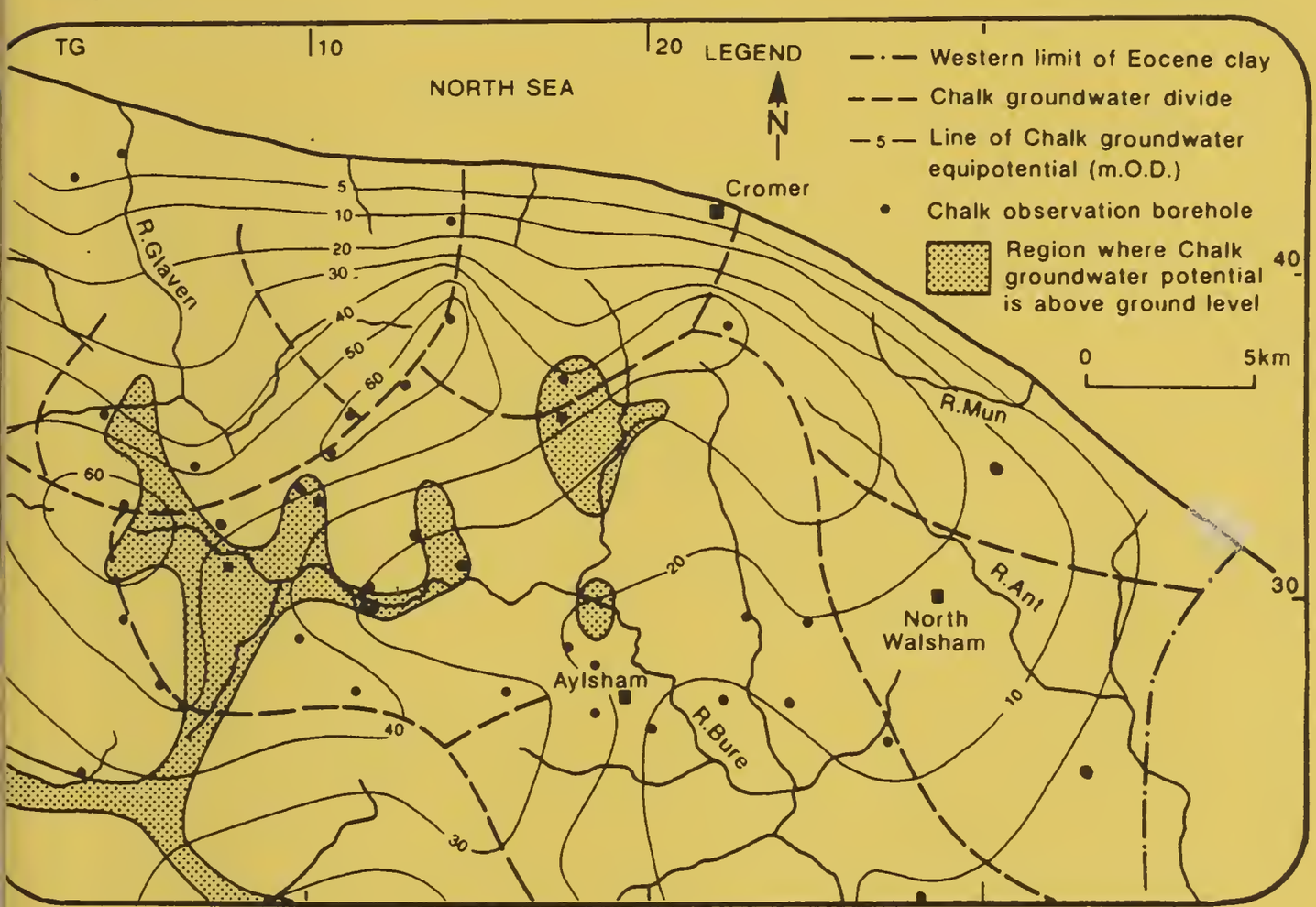
BULLETIN OF THE GEOLOGICAL SOCIETY OF NORFOLK

(FOR ARTICLES ON THE GEOLOGY OF EAST ANGLIA)

NO.41 for 1991



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Hydrogeology of the North Norfolk Chalk Aquifer

Chalk Palaeontology

Elephant Skeleton from the West Runton Freshwater Bed

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Editor: Anthony J. Stuart

Castle Museum
Norwich NR1 3JU
(Telephone Norwich 223644)

Production Editor: Julian E. Andrews

School of Environmental Sciences
University of East Anglia
Norwich NR4 7TJ
(Telephone Norwich 56161, Ext. 2536)

EDITORIAL

Here at last is Bulletin No. 41. We apologize for the long delay in publication of this issue, which has had to await the accumulation of sufficient material.

As is only proper with a new editorship, and taking advantage of the availability of new technology, we have introduced some changes in the layout and print style which we hope will be seen as an improvement. We have also made some modifications to the 'Instructions to Authors', in particular that the style of submitted papers should conform to a new standard for the Bulletin (see below). However, the format and essential character of the Bulletin remain unaltered.

The backbone of this issue, which covers a wide range of topics, is Kevin Hiscock's substantial and scholarly paper on the hydrogeology of the Norfolk Chalk. This is followed by three short articles on Chalk palaeontology and a preliminary account of the recent find of an elephant skeleton in the Cromer Forest Bed.

We are still very short of material for future issues and welcome the submission of papers on any aspect of East Anglian geology.

INSTRUCTIONS TO AUTHORS

If possible, contributors should submit manuscripts as word-processor print out accompanied by a disk copy. We can handle most word-processing formats although PC Word, Wordperfect or ASCII files are preferred. In addition we accept typewritten copy and will consider legible handwritten material.

It is important that the style of the paper, in terms of overall format, capitalisation, punctuation, etc. conforms as strictly as possible to that used in Vol. 41 of the Bulletin. Titles and first order headings should be capitalised, centred and in bold print. Second order headings should be centred, bold and lower case. Text should be 1½ line spaced. All measurements should be given in metric units.

References should be arranged alphabetically in the following style.

BALSON, P.S. & CAMERON, T.T.J. 1985. Quaternary mapping offshore East Anglia. *Modern Geology*, **9**, 221-239.

STEERS, J.A. 1960. Physiography and evolution: the physiography and evolution of Scolt Head Island. In: Steers, J.D. (ed.) *Scolt Head Island (2nd ed.)*, 12-66, Heffer, Cambridge.

BLACK, R.M. 1988. *The Elements of Palaeontology*. 2nd Ed., Cambridge University Press, Cambridge. 404pp.

Illustrations should be drawn with thin dense black ink lines. Thick lines, close stipple or patches of solid black should be avoided as these spread in printing. Original illustrations should, before reproduction, be not more than **175mm by 255mm**. Full use should be made of the first (horizontal) dimension which corresponds to the width of print on the page, but the second (vertical) dimension is an upper limit only. Half tone photographic plates are acceptable when their use is warranted by the subject matter, provided the originals exhibit good contrast.

The editors welcome original research papers, notes or comments, and review articles relevant to the geology of East Anglia as a whole, and do not restrict consideration to articles covering Norfolk alone. All papers are independently refereed by at least one reviewer.

THE HYDROGEOLOGY OF THE CHALK AQUIFER SYSTEM OF NORTH NORFOLK

Kevin M. Hiscock

School of Environmental Sciences,
University of East Anglia,
Norwich NR4 7TJ

ABSTRACT

Hydrogeological properties of the Chalk and Crag aquifers of north Norfolk are discussed based upon available information. To advance understanding of the groundwater flow mechanisms in the Chalk aquifer system, this paper presents the results of an extensive groundwater chemistry study in north Norfolk. Combining the hydrogeological and hydrochemical data has provided an understanding of the Chalk aquifer system. The main findings are that the nature and distribution of the pre-Devensian tills govern aquifer conditions and that the Chalk groundwater becomes more saline eastwards, as the Eocene boundary is approached. In general, the valley zone Chalk groundwaters are modern in age, chemically oxidising in character and contain modern contaminants of a mainly agricultural origin; whereas the interfluvial Chalk groundwaters are old (possibly up to 18,000 years old), chemically reducing in character and of good quality, except for occasional high iron concentrations.

Chalk groundwater in areas covered by Lowestoft Till can be distinguished from Chalk groundwater in areas covered by North Sea Drift by a bicarbonate concentration of 300 mgl^{-1}. Values in excess of this concentration are associated with the carbonate-rich Lowestoft Till.

INTRODUCTION

In eastern England the Chalk aquifer is an important source of groundwater supplying approximately half of the water supply demand. Across the region Quaternary deposits cover the Chalk and the juxtaposition of these deposits influences the underlying aquifer conditions. Such a relationship has been demonstrated in Essex by Lloyd *et al.* (1981) and in Suffolk by Heathcote and Lloyd (1984).

In the north of the region, there are two lithologically distinct pre-

Devensian glacial tills: the North Sea Drift and Lowestoft Till. The occurrence of both glacial tills in north Norfolk results in a complex relationship between the Chalk aquifer and overlying Quaternary deposits.

To provide an understanding of the hydrogeology of north Norfolk, this paper first details existing hydraulic information relating to the Chalk aquifer system (including the Crag aquifer) and then presents and interprets original hydrochemical data collected as part of a regional groundwater chemistry study.

The overall aims of the paper are: firstly, to provide an interpretation of the hydrogeochemical processes operating in the Chalk aquifer in order to deduce the groundwater flow mechanisms; and, secondly, to show how the varying mechanical and mineralogical properties of the pre-Devensian tills influence Chalk aquifer conditions.

GEOLOGY OF NORTH NORFOLK

The area discussed in this paper is shown in Fig.1 and comprises the upper Bure and Wensum catchment areas. The outline geology is simple with Cretaceous Chalk dipping eastwards and north-eastwards, overlain unconformably by Tertiary deposits dipping gently in the same direction. The surface geology of the area is shown in Fig.2, based on the 1:253,440 drift geology map of northern East Anglia. Fig.1 also depicts the western limits of the Eocene Clay and Pleistocene Crag. The lithostratigraphical divisions present in the area are given in Table 1.

Pre-Pleistocene strata

The Chalk, a fine-grained, fissured limestone, attains a thickness of 430 m at Trimingham on the north Norfolk coast and is exposed in the west of Norfolk and along the larger river valleys to the west and north-west of Norwich (Peake and Hancock, 1961). A cored research borehole at Trunch penetrated a total Chalk thickness of 472 m (Bath and Edmunds, 1981). In the higher parts, the Chalk is soft and in places has been subjected to post-depositional solution and deformation during the Quaternary (Rawson *et al.*, 1978). Structurally, the Chalk dips eastwards at about 0.6° in north Norfolk, with a component of dip towards the east-north-east in the east of the region. The upper surface of the Chalk reaches a maximum elevation of 95 m above Ordnance Datum (mOD) about 10 km from its western margin, declining to -154 mOD at

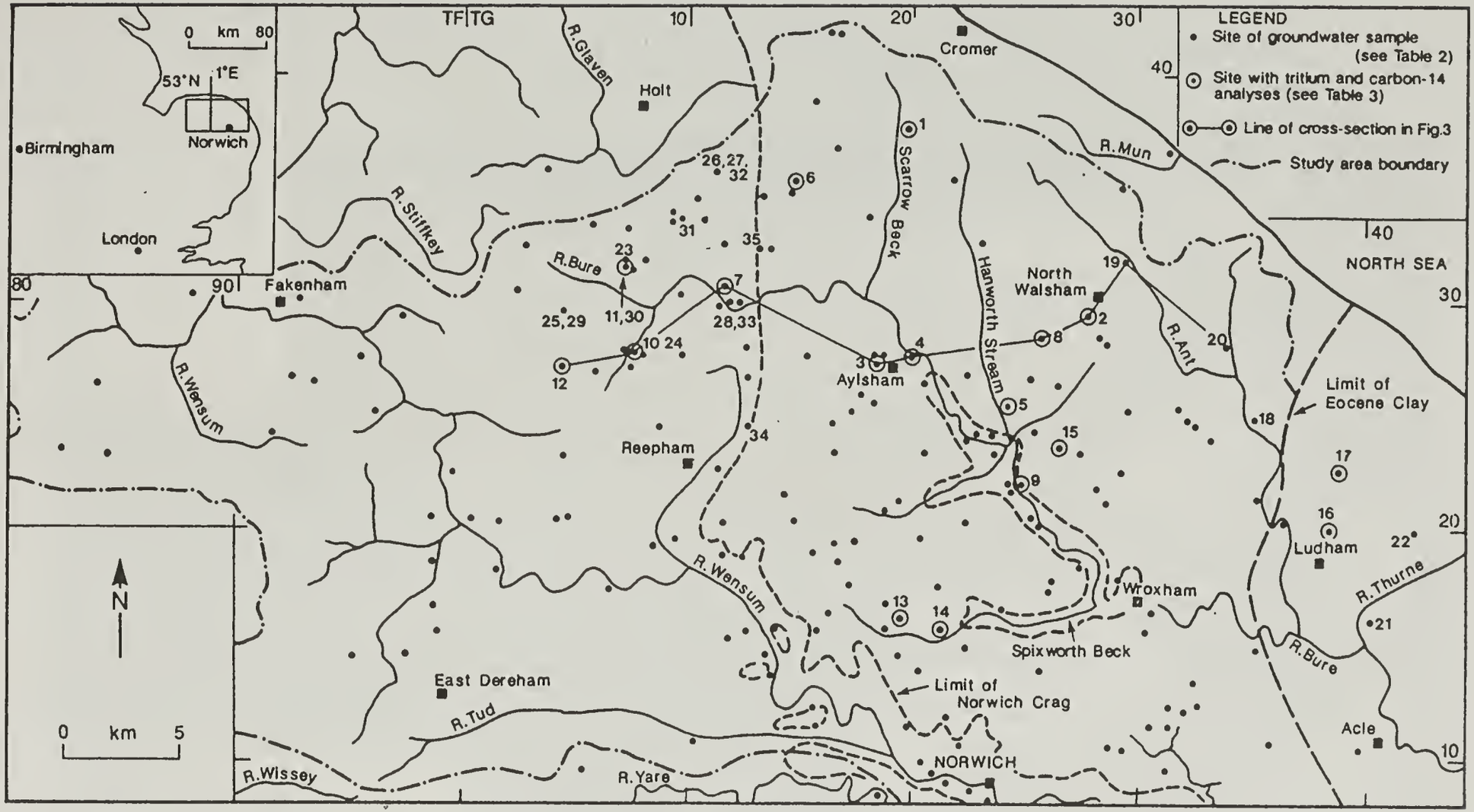

Fig.1. Location map of the upper Bure and Wensum catchmentareas in north Norfolk. The locations of all the Chalk groundwater sampling sites are shown. Numbered sample sites refer to groundwater analyses given in Tables 2 and 3.

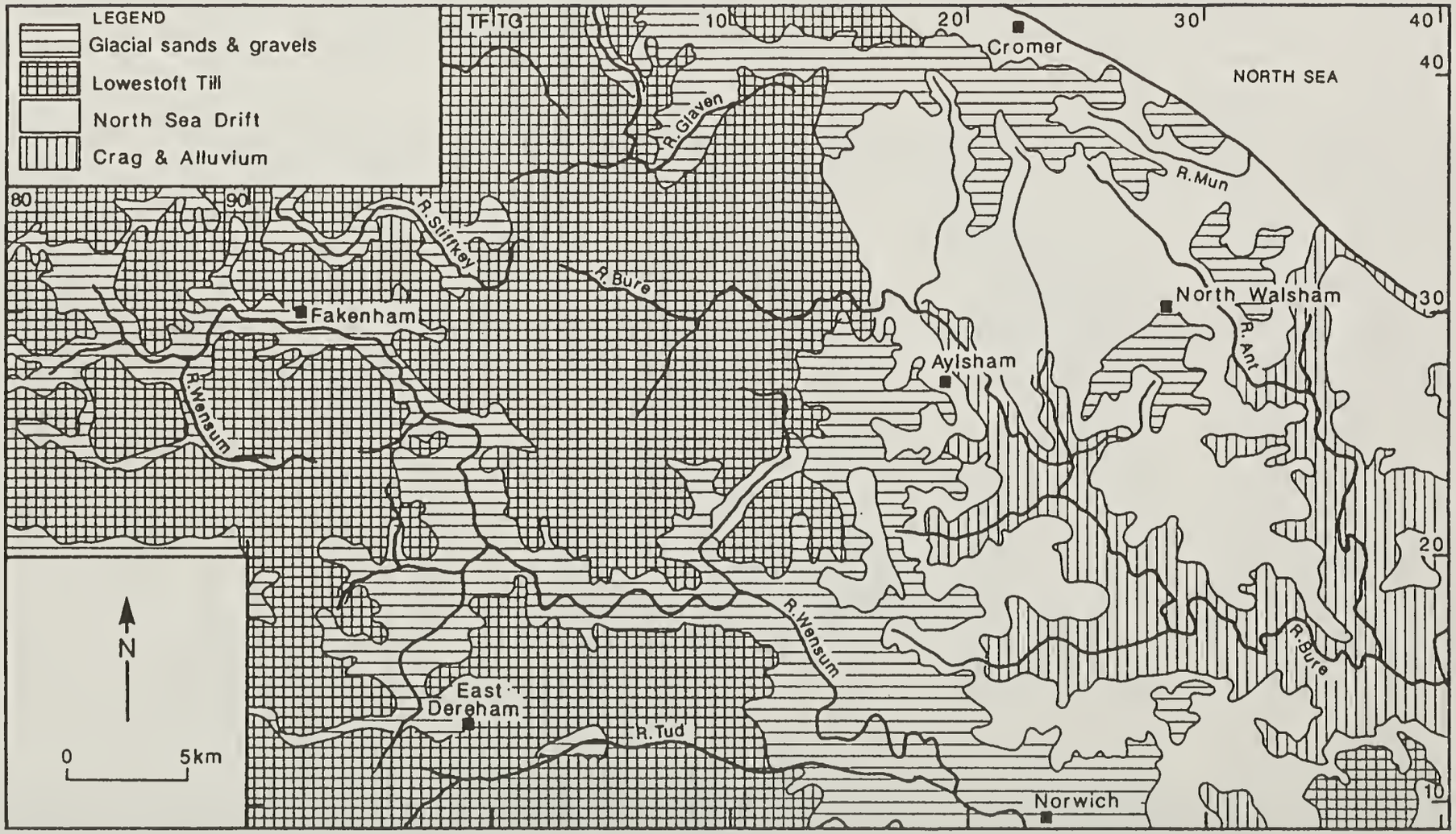

Fig.2. Geology map of north Norfolk showing the regional distribution of Quaternary deposits.

System	Series	Formation	Lithology	Approx. thickness (m)
Quaternary	Holocene	Recent deposits	Alluvium, peat and coastal sand and shingle	<20
	Pleistocene	Coverloam	Silty loess	<2
		Lowestoft Till	Brown calcareous clay with clasts of chalk and flint	15-30 (up to 60)
		Corton Sands	Compact yellow sands	<10
		North Sea Drift	Norwich Brickearth: brown non-calcareous sandy clay with flint	<5
			Cromer Tills: grey silty clay interbedded with sands	<30
		Cromer Forest-bed Formation	Marine and freshwater sands, clays and gravels	5-10
		Norwich and Ludham Crags	Marine sand with shell beds and clay beds with organic mud	0-30
Tertiary	Eocene and Palaeocene	London Clay	Brown-grey, fine grained clay	0-95
		Lower London Tertiaries	Silty sands, silts and clays	14
Cretaceous	Upper Cretaceous	Chalk	Fine grained, fissured lime-stone	<430

Table 1. Geological succession of north Norfolk

Great Yarmouth (Peake and Hancock, 1961).

Lower Tertiary deposits, including the Palaeocene Thanet Sands and Reading beds, are known from Great Yarmouth (Funnell, 1961) and are overlain by 95 m of Eocene Clay. The Eocene Clay thins westwards and comes to rest directly on the Chalk, with its western feather edge at a maximum of 16 km from the present coast. No Upper Tertiary deposits occur in north Norfolk and Baker (1918) concludes that this was a period of extensive erosion, even greater than that which intervened between the Cretaceous and the Palaeocene.

Quaternary deposits

The succession of early Pleistocene deposits in East Anglia is described by Funnell and West (1977). The Ludham Crag comprises 18 m of coarse shelly sands occurring in the east of the region. The succeeding Norwich Crag occurs in the vicinity of Norwich, throughout east Norfolk and into north-east Suffolk, and is a marine sand with shell beds, clay beds and gravelly horizons. The Norwich Crag is about 18 m thick at Ludham and 12 m thick at Bramerton, south-east of Norwich (Funnell *et al.* 1979). The Cromer Forest-bed Formation consists of freshwater and marine sediments and is exposed on the north Norfolk coast reaching a maximum thickness of about 10 m (West, 1980).

The late Pleistocene deposits of Norfolk represent a period dominated by a major ice age. In brief, temperatures began to fall at the end of the Beestonian Stage about 700,000 years Before Present (BP) and the cycle of glaciations and interglacials continued until the end of the Devensian Stage, 10,000 years BP. The present Flandrian Stage is a continuing interglacial period.

The first authoritative account of the glacial deposits of the Norwich area is given by Wood and Harmer (1868). Subsequent contributions have been made by Reid (1882), Soloman (1932), Baden-Pŏwell (1948), West and Donner (1956), Krinsley and Funnell (1965), Banham (1968), Kazi and Knill (1969), Cox and Nickless (1972), Banham *et al.* (1975), Hopson (1984), Boulton *et al.* (1984) and Hart *et al.* (1990).

The glacial deposits of the study area can be ascribed to a single complex glacial stage, the Anglian Stage, when two ice lobes entered the region. The ice advance from the west deposited the Lowestoft Till, and the advance from the north-east deposited the North Sea Drift. A third till, the Marly Drift, is found in the north of the region and is highly laminated, like

the North Sea Drift except that its dominant laminae are of crushed and reconstituted Chalk. The three lithofacies simply reflect different sources of supply. The first, the Jurassic lowlands around the Fenland basin and the Chalk of west and central Norfolk, and the second and third, the Chalk of north-east Norfolk. All three contain various sands, clays and organic materials from the various earlier or preglacial Pleistocene deposits (Boulton *et al.*, 1984).

The compositional studies of Perrin *et al.* (1979) showed that the tills are difficult to distinguish on the basis of mineralogy, each containing illite, kaolinite and montmorillonite. However, the Lowestoft Till contains more clay and carbonate debris and less sand than the North Sea Drift.

Within the area shown in Fig.2 the Lowestoft Till occupies the upper Bure catchment area and is present in the interfluve areas of the Wensum catchment. Typically, the deposit is 15-30 m thick, with 60 m possible within sub-glacially eroded channels. The North Sea Drift is present in the north and east of the Bure catchment and forms the Cromer Ridge complex (Banham, 1975). The deposit is typically 30 m thick and contains the Cromer Tills. The inland extension of the Cromer Tills identified on the north Norfolk coast is the Norwich Brickearth, a deeply weathered, brown sandy clay, about 5 m in thickness. West of Norwich the boundary between the Lowestoft Till and North Sea Drift is obscurred by thick fluvio-glacial outwash deposits that extend in a line from Norwich to Holt.

Following the Anglian glaciation the climate ameliorated during the Hoxian interglacial. In the Wolstonian cold period, no till was deposited in East Anglia (Shotton *et al.*, 1977). The succeeding Ipswichian interglacial is associated with fluviatile terrace deposits in present river valleys, indicating that the present East Anglian river system was essentially established by the beginning of the Ipswichian Stage.

During the last, Devensian glaciation the principal effect in Norfolk was the widespread development of permafrost conditions (Williams, 1969). This resulted in the formation of patterned ground and the deposition of a widespread, near-surface wind-blown silty deposit, or Coverloam. Catt *et al.* (1971) describe the Coverloam as a uniform cover up to 2 m thick that is restricted to east Norfolk and north-east Suffolk, and is derived from the Devensian Till of north-west Norfolk.

Major melting of the Devensian ice sheet began about 11,000 years BP

with the climate recovering during the present Flandrian (Holocene) interglacial. Recent deposits include peats, clays and alluvium which occupy Broadland and the lower reaches of the main river valleys in the east of the region.

To illustrate the complex relationship between the Pleistocene deposits in north Norfolk, Fig. 3 is a geological cross-section drawn through the rivers Bure and Ant catchments along the irregular line shown in Fig. 1. The lithological details shown are contained in the Aylsham Sheet Well Catalogue (Institute of Geological Sciences, 1968) and other existing borehole records. In constructing the cross-section, uncertainties in the driller's logs have been interpreted in the context of the regional geology. For the sake of clarity in depicting the Pleistocene deposits, only the top 20 m of the Chalk have been shown; although the total depth of each borehole is indicated in Fig. 3.

The geological cross-section presented is a simplification of the real situation in that the glacial till deposits are very heterogeneous in nature and are unlikely to appear as the uniform, continuous till sheets shown. However, the section does illustrate the gradual easterly dip of the Chalk surface, the relative positions of the Pleistocene deposits and the way in which the river Bure has incised the glacial deposits in the vicinity of Aylsham.

HYDROGEOLOGY OF NORTH NORFOLK

Existing information

An assessment of the groundwater resource potential of the district, together with information on groundwater quality, is contained in the Section 14 survey compiled by the East Suffolk and Norfolk River Authority (1971). A summary of the hydrogeological properties of the various aquifer units and information relating to groundwater levels in the region are presented on the Hydrogeological map of northern East Anglia (Institute of Geological Sciences, 1976). Figure 4 represents groundwater conditions in May 1981 and was compiled using unpublished data now held by the National Rivers Authority. Groundwater flow in the study area forms part of the Eastern province regional groundwater flow system defined by Downing *et al.* (1987). The Chalk is the dominant hydrogeological unit.

Well Catalogue no.	147/138b	597	146	37	–	76	24d	–	–
Total borehole depth (m)	91.5	80.0	36.9	42.7	38.2	53.4	122.0	85.0	45.5
Static water level (mOD)	52.00	–	26.84	22.57	0.10	25.01	24.69	4.52	1.16
Sample no. (see Fig.1)	12	10	7	3	4	8	2	19	20

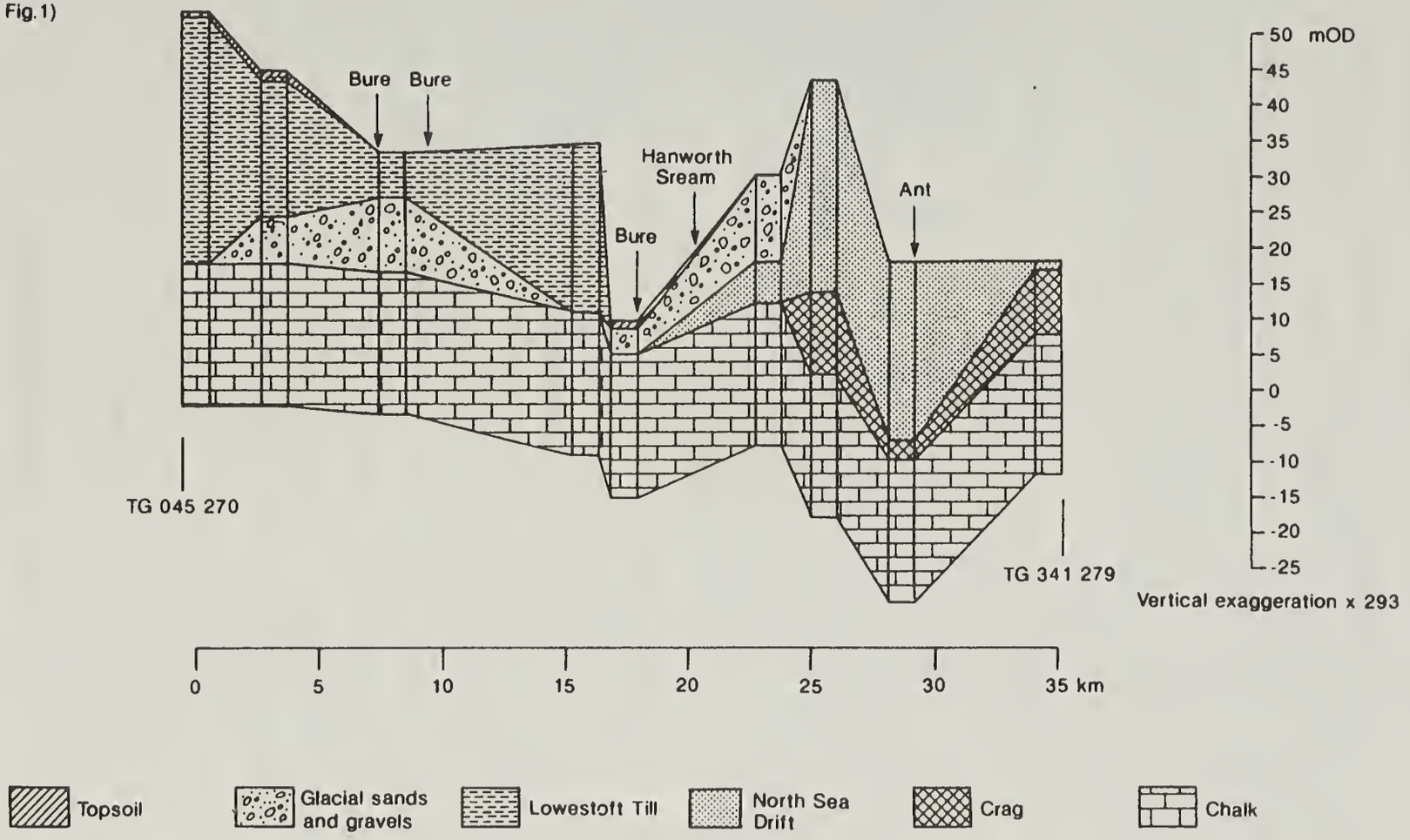

Fig.3. Geological cross-section through the rivers Bure and Ant catchments between Guestwick and East Ruston in north Norfolk. The line of the section is shown in Fig.1.

Chalk aquifer conditions and boundaries

Examination of contours on the Chalk aquifer equipotential surface shown in Fig.4 reveals a close similarity between the groundwater divides and topographically high ground. The groundwater catchments correspond approximately to the surface catchment areas. In the lower Bure, Ant and Thurne catchments, the Chalk is confined beneath the Eocene clay, with a groundwater level, or piezometric head, at about 0 mOD. Apartfrom minor abstractions in the Great Yarmouth area, there is no natural discharge from this confined part of the aquifer; thus, groundwater flow east of the Eocene boundary is virtually absent.

Fluctuation of the Chalk piezometric head is greatest in the region of the groundwater divides, with an annual difference of typically 1 m. The groundwater level fluctuation within the valley zone is no more than 0.5 m.

Comparison of Fig.4 with Fig.2 shows that different aquifer conditions are associated with the distribution of Quaternary deposits. Overflowing artesian groundwater conditions occur in the upper Bure catchment in regions of thick Lowestoft Till and North Sea Drift deposits. These areas are reflected in the peaty soils found along valleys where such groundwater conditions prevail. Unconfined conditions occur within the valley zone to the north-west and north of Norwich where either the Chalk crops out or there is a thin cover of Norwich Crag, Norwich Brickearth or glacial sands and gravels.

As elsewhere, the lower boundary of the Chalk aquifer does not correspond with the maximum depth of the sequence (Headworth *et al.*, 1982). Investigations in north Norfolk using geophysical borehole logging equipment and point dilution tracer experiments proved that the extent of the effective Chalk aquifer is variable. In the interfluve areas where the glacial till sequence is thickest, there is only minor fissuring of the Chalk to a depth of about 10 m. In contrast, where the Chalk is unconfined in the valley zone, the Chalk is fissured to a depth of about 20 m. The fissures are formed by solution of the Chalk along fractures and bedding planes.

Chalk aquifer properties

The largest producing boreholes in Norfolk are at Thorpe St. Andrew [TG 253 084] in the Yare valley. Here, a 610 mm diameter public supply borehole penetrating 55.7 m of the Upper Chalk beneath glacial sands and gravels yielded 186 $1s^{-1}$ (litres per second) for a water level drawdown in the

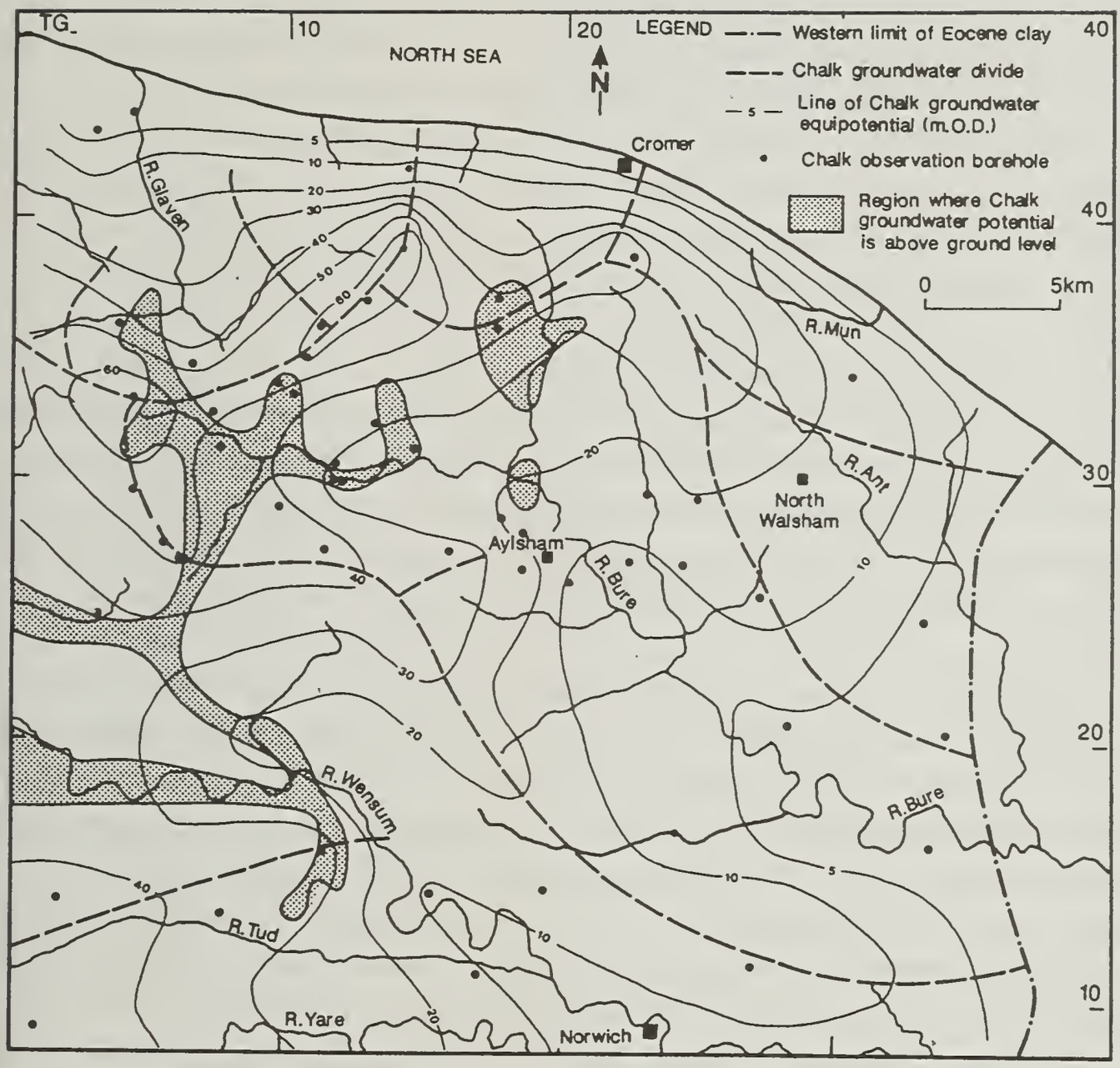

Fig.4. Hydrogeology map of north-east Norfolk. Groundwater conditions in the Chalk aquifer are as measured in May 1981.

boreholes of only 15 m. More typical borehole yields are in the range 35 to 75 ls^{-1}. The difference in yields is attributable to differences in the transmissivity of the Chalk in valleys and interfluves, respectively. At Thorpe St Andrew, a chalk transmissivity of 2680 m^2d^{-1} (square metres per day) is recorded (Toynton, 1983), yet values of less than 100 m^2d^{-1} can be expected in the interfluve areas (Ineson, 1962; Song and Atkinson, 1991).

The high chalk transmissivity associated with valleys may have been influenced by one of the following: firstly, north-west-trending zones of shear fracturing within the Chalk may have controlled the regional drainage pattern throughout the Quaternary; secondly, the Chalk close to outcrop in valleys may have been subject to near-surface stress release, resulting in the opening of fissures on bedding surfaces (Ineson, 1962; Price, 1987); and thirdly, a concentration of groundwater flow towards valleys may have lead to enhanced solution of the Chalk along existing fissures (Price, 1987). However, the extent to which geological and hydrogeological conditions have influenced the present-day surface drainage network, and thus the distribution of the zones of enhanced transmissivity within the Chalk, is speculative (Straw, 1979).

Analysis of base flow and groundwater recession data for the period 1959-1968 for the upper Bure and Wensum catchments by Toynton (1983) gave values for mean transmissivity of 373 and 685 m^2d^{-1} and values for mean storage coefficient of 0.077 and 0.064. Again, an association with Quaternary deposits is observed. The wider development of unconfined Chalk conditions and the greater area of Lowestoft Till cover in the Wensum catchment, relative to the Bure catchment,are possible reasons, respectively, for the higher transmissivity value and lower storage coefficient in the Wensum catchment.

Toynton (1983) also shows that the Chalk fracture pattern imparts hydraulic anisotropy to the aquifer. At Corpusty, in the upper Bure catchment, Atkinson (1981) proves such a situation with transmissivity values ranging between 309 and 2650 m^2d^{-1}, with the maximum transmissivity oriented in an east-north-east direction, parallel to the river Bure valley.

In north-east Norfolk there is a scatter of almost forty boreholes showing anomalous depths of Quaternary deposits. In general, the boreholes are not located in the bottom of the present valleys and it is not easy to identify an obvious pattern to which they belong. According to Woodland (1970), the main channels run approximately from east to west and terminate

at the margin of the ice sheets that occupied this part of East Anglia. Cox and Nickless (1977) support this observation. It is arguable as to whether or not the Chalk in the vicinity of a buried channel has a high transmissivity. Foster and Robertson (1977) suggest not, believing the zone of more permeable Chalk to have been removed by sub-glacial erosion. Conversely, the hydrostatic pressure developed beneath the ice sheet may have fractured the Chalk along planes of weakness that already existed and so promoting aquifer development. Some evidence for this view is given by Atkinson (1981) who reports high transmissivities approaching 2000 m^2d^{-1} in the vicinity of a buried channel at Saxthorpe in the upper Bure Valley.

Crag aquifer definition

The Crag aquifer is an important source of groundwater in the east of north Norfolk, supplying local, mostly agriculturaldemand. Yields are generally less dependable than those from the Chalk. The type of well or borehole used for abstraction must be taken into account when considering yields from the Crag. Older dug wells and collector systems are shallow and of simple construction. Sand entry can be a problem in such systems and only low pumping rates (2-4 ls^{-1}) are achievable. Gravel-packed or screened boreholes give higher yields. At Ludham Pumping Station [TG385 198] a screened borehole 59.7 m deep yielded 40 ls^{-1} on test for a drawdown of 11.9 m.

At Ludham, the groundwater is abstracted from the bottom 6 m of the aquifer in order to draw from a layer consisting mainly of sand and shell fragments. Well point systems, used almost exclusively for spray irrigation, consist of a series of narrow diameter perforated tubes connected by a suction header to a single pump. The yield of an individual installation depends on the number of well points, but is likely to be in the range 10 to 40 ls^{-1}. Analysis of pumping test results by the National Rivers Authority (pers. comm.) suggests transmissivity and storage coefficient values for the Crag aquifer of between 10^2 and 10^3 m^2d^{-1} and 10^{-4} and 10^{-2}, respectively. Experience in the use of the Crag aquifer for water supply is documented by Forbes (1952) and Clarke and Phillips (1984).

Groundwater flow in the Crag is intergranular, with groundwater yields depending on the coarseness of the sand and gravel fraction. The Crag partly resembles the Chalk in that it consists of layers of varying permeability. The precise interbedding of clays and sands has only been measured at a few

sites, but there is probably only little lateral continuity of each horizon. The degree of lateral continuity will promote and control horizontal groundwater movement. The existence of such layers may promote perched aquifer conditions.

In the west of the area, the Crag is in hydraulic continuity with the Chalk. In the east, where the Crag is separated from the Chalk by the Eocene Clay, Crag water levels are generally higher than those in the Chalk. Locally, Crag water levels have been lowered below sea-level by pumped drainage of the marshes.

Other hydrogeological units

In Norfolk, the Eocene is essentially a clay formation and appears to be entirely argillaceous to the west of Great Yarmouth. The Eocene Clay is not water bearing and forms an aquiclude between the Crag and Chalk aquifers.

Only very minor supplies have been obtained in the past from the Lowestoft Till and North Sea Drift. However, the hydrogeological behaviour of the glacial tills is important with respect to their potential for transmitting recharge to the underlying aquifers. Furthermore, where glacial till occupies a buried channel, there may be disruption of the regional hydrogeological regime. Buried channels that are completely filled with Lowestoft Till may form barriers to lateral groundwater flow, while those that include North Sea Drift may increase groundwater flow and enhance groundwater storage. Laboratory measurements of matrix hydraulic conductivity of boulder clay samples by Toynton (1979) and Lloyd *et al.* (1981) are in the range 10^{-6} to 10^{-4} md^{-1} (metres per day), although field values are likely to be one or more orders of magnitude higher than this (Sharp, 1984).

Glacial sands and gravels, taken together with the Crag and recent Quaternary formations, constitute a substantial, if complex, unconfined groundwater resource. The deposits have a high groundwater storage and, in the west of the district, where there is hydraulic continuity with the Chalk, this storage is important in controlling recharge to the underlying Chalk aquifer. East of the Eocene Clay boundary this resource discharges at the marshland fringe and into side valleys.

Interesting hydrogeological conditions occur near the east coast where Holocene deposits are liable to saline intrusion where pumped drainage of the marshes has reduced groundwater levels to around or below sea-level. Present

information is insufficient to determine the inland extent of the brackish water, but a survey by Downing (1966) in the Hickling-Horsey area of broadland found that fresh groundwater is present beneath topographically higher ground with saline water at depth.

HYDROCHEMISTRY OF NORTH NORFOLK

Previous studies

Mention of the hydrochemistry of Chalk groundwaters in north Norfolk is contained in Baden-Powell (1948) who noted that Chalk groundwaters below glacial till covered areas of Norfolk do not have the high non-carbonate hardness and chloride (Cl) content characteristic of Chalk groundwaters in Suffolk. The line separating the two types of ground water coincides with the boundary separating the glacial till into a chalky drift over Norfolk and a chalky-Jurassic drift over Suffolk. Earlier, Woodland (1946) stated that the partial pressure of carbon dioxide (PCO_2) in the sandy soils of Breckland is low and that, consequently, the carbonate hardness of underlying Chalk groundwater is low, of the order of 100 - 150 mgl^{-1} (milligrams per litre). More recently, Rodda *et al.* (1976), in accordance with Ineson and Downing (1963), noted that the boundary between boulder clay (Lowestoft Till) and sandy glacial drift (North Sea Drift) in north Norfolk is marked by the 200 mgl^{-1} carbonate hardness value for Chalk groundwater. Additionally, the iron chemistry of Chalk groundwaters in north Norfolk is discussed by Song and Atkinson (1985).

Present study - sampling programme and data presentation

Groundwater samples were collected from agricultural and public water supply Chalk boreholes, drift wells and piezometers, and Crag wells and boreholes during the period 1982-1985. The distribution of sampling sites is shown in Fig.1.

Samples were collected in 250 ml glass bottles for major ion analyses, 60 ml polypropylene bottles for minor ion analyses and 20 ml vials, acidified with a 2 ml solution of 50% nitric acid, for iron (Fe) analysis. Chemical analyses were performed using the methods described by Lloyd and Heathcote (1985). Field measurements of pH, electrical conductivity (EC), temperature and redox potential (Eh), the latter on flowing samples only, were made using standard procedures.

Samples were also collected for analysis of tritium and carbon-14 activity using procedures described, respectively, by Otlet (1977) and Lloyd and Heathcote (1985). Particular attention is needed to avoid contamination of the samples with atmospheric tritium and carbon-14.

The chemical analyses and field measurements are presented in Tables 2 to 3 and Figures 5 to 8. Table 2 contains minor ion data (including nitrate, NO_3), well-head measurements, a calculated value of PCO_2 (given in bars) and information pertaining to the nature of the sample. Table 3 contains tritium and carbon-14 data and corrected groundwater ages for Chalk and Crag groundwaters. The major ion data, as well as Fe concentrations are depicted graphically as pattern diagrams (in the style of Stiff, 1951) and as vertical bar graphs in Figures 5 to 8.

Errors typically arise in the laboratory and field measurements. The major ion concentrations are within ± 1 mgl^{-1}, the minor ions within ± 0.05 mgl^{-1} and the iodide value within ± 0.5 μgl^{-1} (micrograms per litre). The pH value is accurate to ± 0.02, EC to ± 5 μScm^{-1} (microsiemens per centimetre), temperature to ± 0.05°C and Eh to ± 5 mV (millivolts). Combined field and laboratory errors in the tritium determination give on accuracy of ± 2 TU (tritium units). The carbon-14 activity is given in terms of percent modern carbon (pmc) with an error associated with the counting statistics of about ± 0.6 pmc.

The raw carbon-14 data have been adjusted for dilution by soil and aquifer carbonate of lithic origin by the method given by Lloyd and Heathcote (1985) and Bishop and Lloyd (1991) to obtain corrected groundwater ages. The measurement error for each carbon-14 determination has been used to indicate the minimum error in each corrected groundwater age, as shown in Table 3. Further errors are likely to arise due to fractionation effects and contamination with atmospheric carbon-14 during sample collection.

The anomalous iodide content of 180 μgl^{-1} in sample 9 is probably derived from an anthropogenic source, for example detergent. In sample 10, which is an overflowing borehole sample, the relatively high sulphate (SO_4) concentration is due to the effect of high SO_4 water, present at depth in the aquifer, mixing with SO_4-reduced water in the top region of the aquifer. A depth sample from 87 m (55 m below the Chalk surface) recorded a SO_4 value of 106 mgl^{-1}, while sample 24 taken from a depth of 20 m in an adjacent drift piezometer, recorded a SO_4 value of 0 mgl^{-1}. The measured tritium value for

Table 2. Minor ion analyses, well head measurements and calculated parameters for north Norfolk Chalk and Crag groundwaters

Hydrochemical facies	Sample no[1] (Fig.1)		NO_3	Sr	SiO_2	I	EC	Eh	Temp	pH	$pPCO_2$[2]
			mgl^{1}	mgl^{-1}	mgl^{-1}	μgl^{-1}	μScm^{-1}	mV	°C		
Chalk waters											
Ia	4	P	11	0.71	11.6	6.0	780	380	10.3	7.52	2.17
	5	P	13	0.65	12.6	5.4	945	375	10.4	7.20	1.79
	9	S	62	0.64	11.8	180.0	1000	-	10.5	7.25	1.71
	14	S	7	5.00	10.5	5.4	720	290	9.3	7.38	2.06
Ib	3	P	0	0.31	9.8	5.6	460	55	10.2	7.85	2.64
	7	P	0	0.13	9.6	6.5	490	100	10.0	7.84	2.61
	13	P	0	0.56	11.1	3.5	450	100	10.4	7.80	2.66
	15	P	0	1.18	14.3	9.0	650	135	10.5	7.25	1.84
IIa	1	P	0	0.65	18.2	6.2	500	75	9.8	7.80	2.50
	2	P	0	1.63	15.8	9.6	650	260	10.5	7.70	2.39
	6	P	0	0.37	11.3	6.5	600	119	10.4	7.40	2.06
	8	P	0	0.26	14.3	5.0	380	130	9.7	7.75	2.72
IIb	10	A	0	0.52	13.3	12.0	850	90	10.7	7.60	2.12
	11	A	0	0.87	15.6	5.8	500	55	7.1	7.50	2.13
	12	P	0	0.53	19.7	3.8	575	150	9.9	7.45	2.01
III	18	S	0	2.08	19.9	7.2	750	-	8.9	7.80	2.51
	19	P	0	0.68	14.6	10.2	730	110	10.6	7.33	2.03
	20	P	0	2.76	22.0	12.7	960	160	9.4	7.70	2.42
Crag waters	16	P	0	0.60	18.0	4.6	540	130	10.3	7.80	2.56
	17	P	104	0.50	22.0	6.1	880	295	10.8	7.10	2.23
	21	P	20	0.53	13.1	2.4	790	335	10.0	7.50	2.09
	22	S	91	0.28	5.6	20.8	960	-	10.4	6.90	1.64
Drift waters											
Lowestoft till	23	S	0	0.40	14.8	6.6	505	-	8.5	7.20	1.75
	24	S	0	0.60	15.6	7.4	640	-	10.0	7.18	1.73
	25	S	0	0.33	17.1	6.0	440	-	8.7	7.40	2.07
North Sea Drift	26	S	0	0.33	14.1	10.6	720	-	8.9	6.80	1.64
	27	S	0	0.71	18.0	9.7	800	-	9.0	7.80	2.60
	28	S	0	0.53	13.3	5.8	690	-	8.8	7.48	2.14

Notes: 1. P indicates a pumped sample
A is an overflowing, artesian sample
S is a static, depth sample

2. $pPCO_2 = -\log_{10}PCO_2$

Table 3. Tritium, carbon-14 and corrected groundwater age determinations for north Norfolk Chalk and Crag groundwaters

Sample no.	Tritium activity (± 2TU)	^{14}C content (% modern carbon)	Corrected age (years BP)	Hydrochemical facies
1	1.5	40.6 ± 0.6	2,700 ± 60	IIa
2	9.9	39.3 ± 0.6	750 ± 50	IIa
3	4.2	37.4 ± 0.6	2,500 ± 60	Ib
4	22.5	53.5 ± 0.6	MODERN	Ia
5	39.0	61.9 ± 0.6	MODERN	Ia
6	12.1	34.8 ± 0.5	2,800 ± 50	IIa
7	7.6			Ib
8	3.9			IIa
9	34.5			Ia
10	23.6?			IIb
11	5.1	3.9 ± 0.1	18,000 ± 1,000	IIb
12	10.1	47.5 ± 0.8	1,800 ± 20	IIb
13	6.4			Ib
14	10.9			Ia
15	9.3			Ib
16*	2.8	29.5 ± 0.8	500 ± 50	-
17*	12.3			-

* Crag groundwater sample

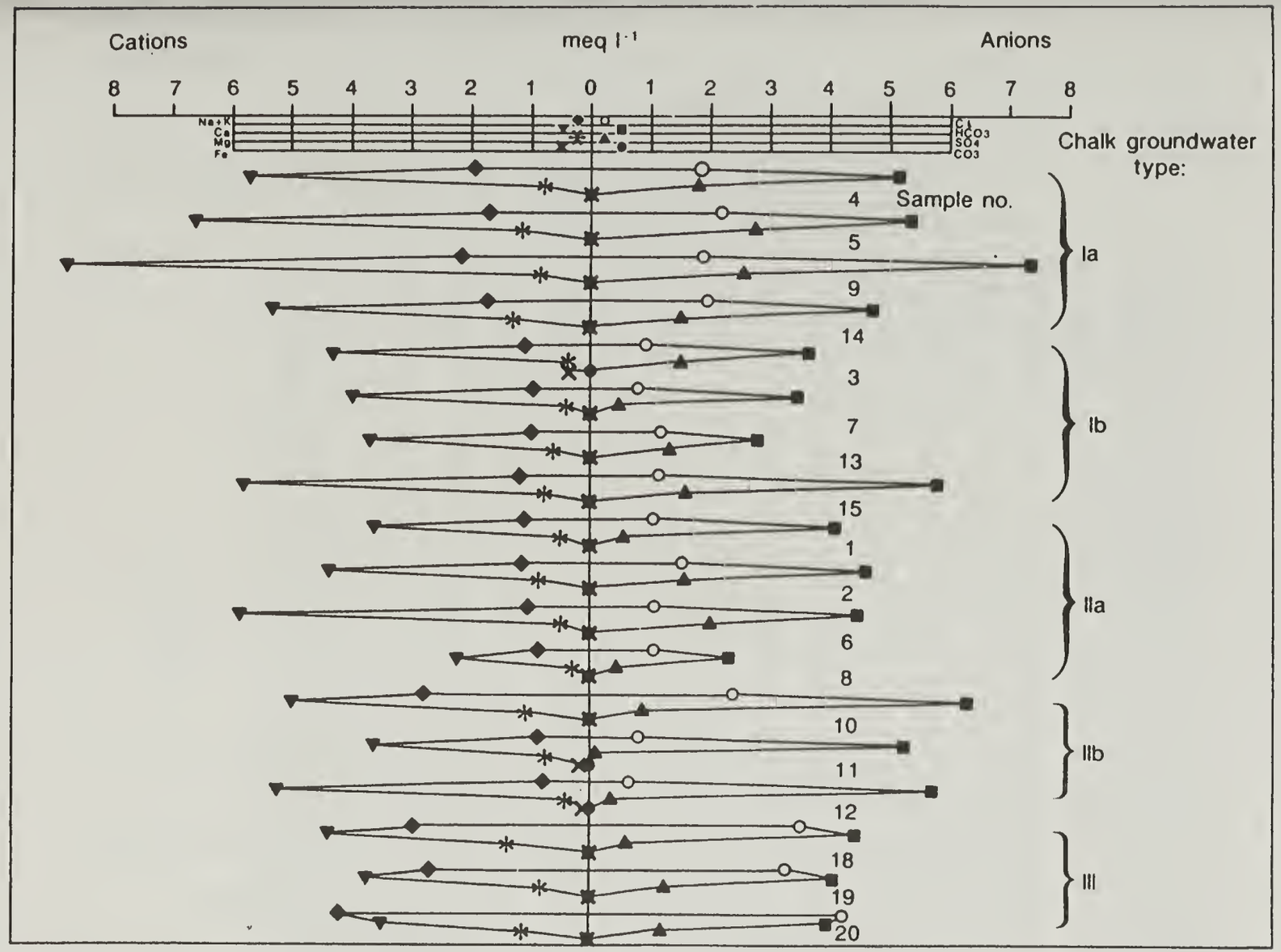

Fig 5. Pattern diagram representing major ion analyses of Chalk groundwaters in north Norfolk. The units are milliequivalents per litre (meq l^{-1}) to convert to milligrams per litre (mg l^{-1}) multiply by the atomic weight of the determinand and divide by its valence number.

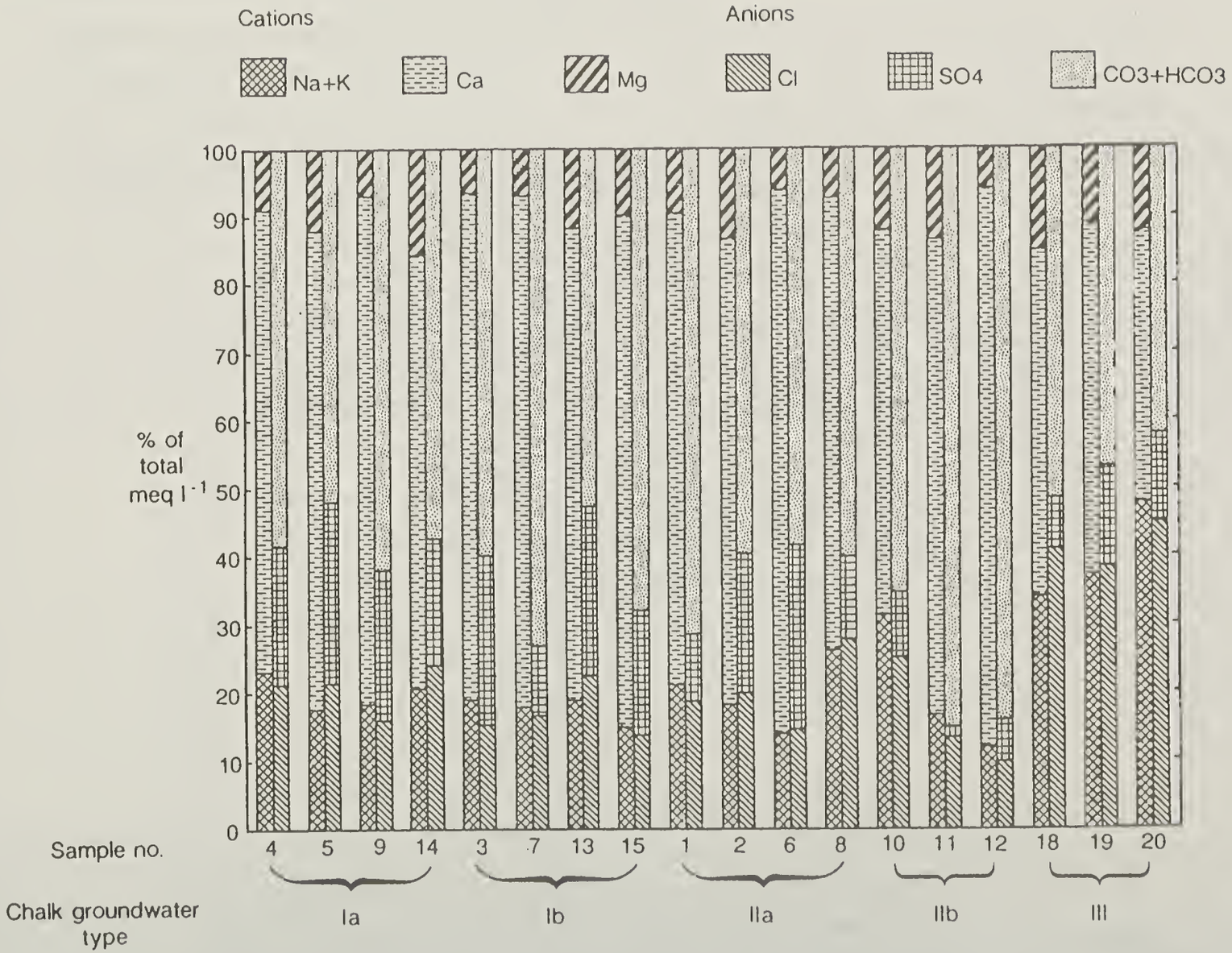

Fig.6. Vertical bar graph representing major ion analyses of Chalk groundwater in north Norfolk in terms of the percentage of total milliequivalents per litre (meq l^{-1}).

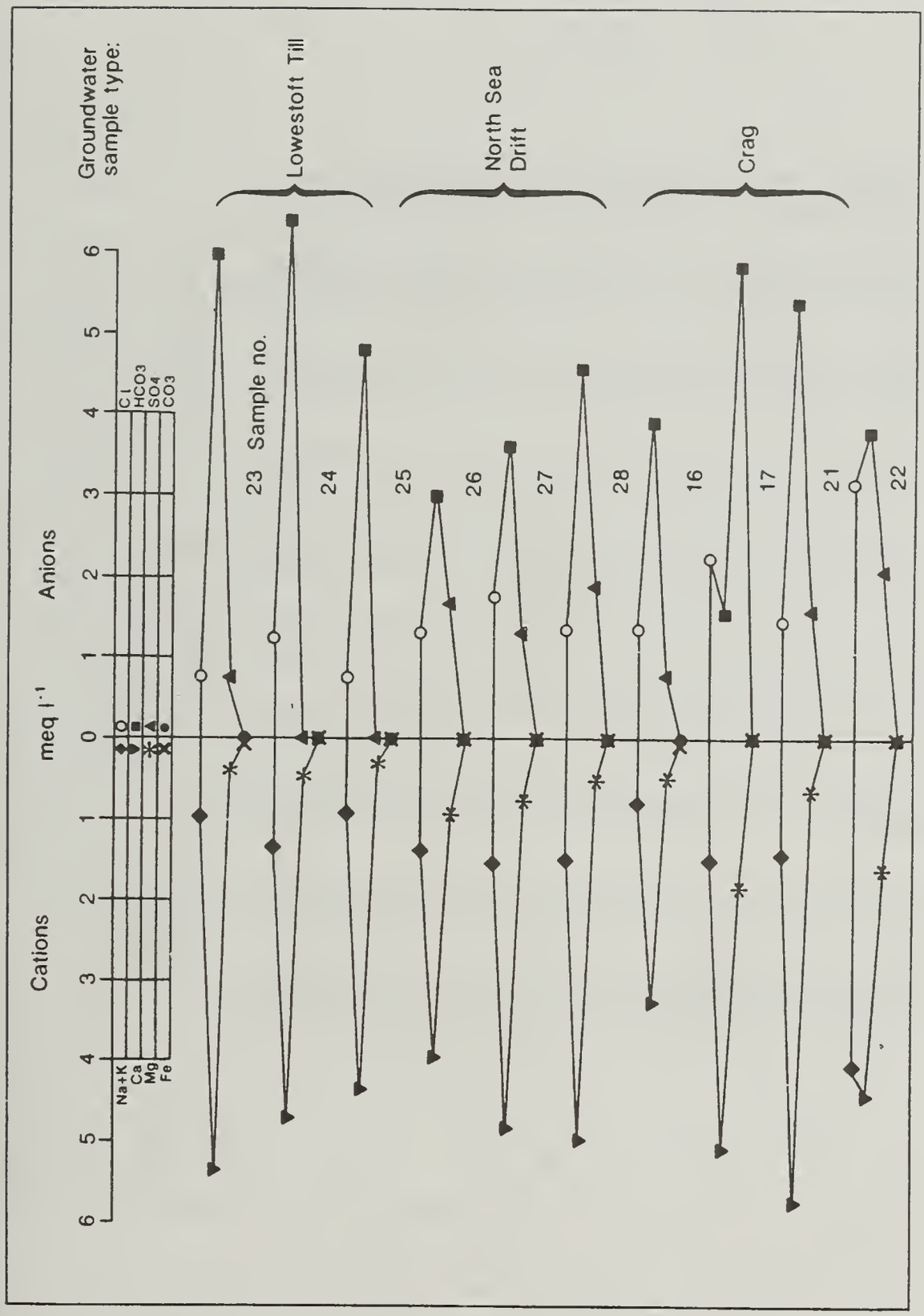

Fig.7. Pattern diagram representing major ion analyses of drift and Crag groundwaters in north Norfolk. See Fig. 5 for explanation of units used.

Fig.8. Vertical bar graph representing major ion analyses of drift and Crag groundwaters in north Norfolk in terms of the percentage of total milliequivalents per litre (meq l^{-1}).

sample 10 of 23.6 TU is erroneous given the absence of NO_3 for this sample and the hydrogeological situation.

Distribution of hydrochemical facies

The hydrochemical data collected in the present study were used to classify the groundwater into hydrochemical facies, or types. This method, developed by Back (1961) is convenient for referring to identifiable groups of samples with a similar water composition; although it is simplistic given that hydrochemical processes are continuous. Generally, the Chalk groundwaters can be described as calcium-bicarbonate ($Ca\text{-}HCO_3$) in composition and the Crag groundwater as calcium-bicarbonate-sulphate ($Ca\text{-}HCO_3\text{-}SO_4$) in composition.

The distribution of the Chalk groundwater facies is shown in Fig.9. There is a broad division of Chalk groundwater between Type I water, corresponding to the valley zone, and Types II and III, associated with interfluvial areas. This division was used in regions with few or no samples to assist in defining the boundary between hydrochemical facies.

Type Ia. This facies is found in the Wensum catchment west of Fakenham and in the valley zone to the west and north-west of Norwich, where the Chalk is either exposed or covered by a thin layer of Crag, Norwich Brickearth or sands and gravels. HCO_3 (300-450 mgl^{-1}), SO_4 (50-130 mgl^{-1}), Cl (40-100 mgl^{-1}) and NO_3 (0-120 mgl^{-1}) concentrations are all relatively high in Type Ia water, with SO_4, Cl and NO_3 contributed by an anthropogenic, mainly agricultural, source.

Supporting evidence that Type Ia is a modern groundwater is provided by the environmental isotopic data. Samples 4, 5 and 9 have tritium values of 22.5, 39.0 and 34.5 TU suggesting a post- 1954 origin for these groundwaters. Additionally, samples 4 and 5 have modern, corrected carbon-14 ages.

Type Ib. This facies occupies areas of the valley zone where glacial sands and gravels exist at the margin of the Lowestoft Till, and where the North Sea Drift thins along the lower slopes of the Cromer Ridge complex to the east and north-west of Aylsham. Ca (70-120 mgl^{-1}) and HCO_3 (200-350 mgl^{-1}) concentrations are lower than for Type Ia, and SO_4 (20-80 mgl^{-1}) and Cl (25-50 mgl^{-1}) concentrations, although lower, indicate an agricultural source. NO_3, normally associated with such inorganic contamination, is undetected.

Type IIa. This facies is restricted to the high ground composed of North Sea Drift along the Cromer Ridge complex in the north of the Bure

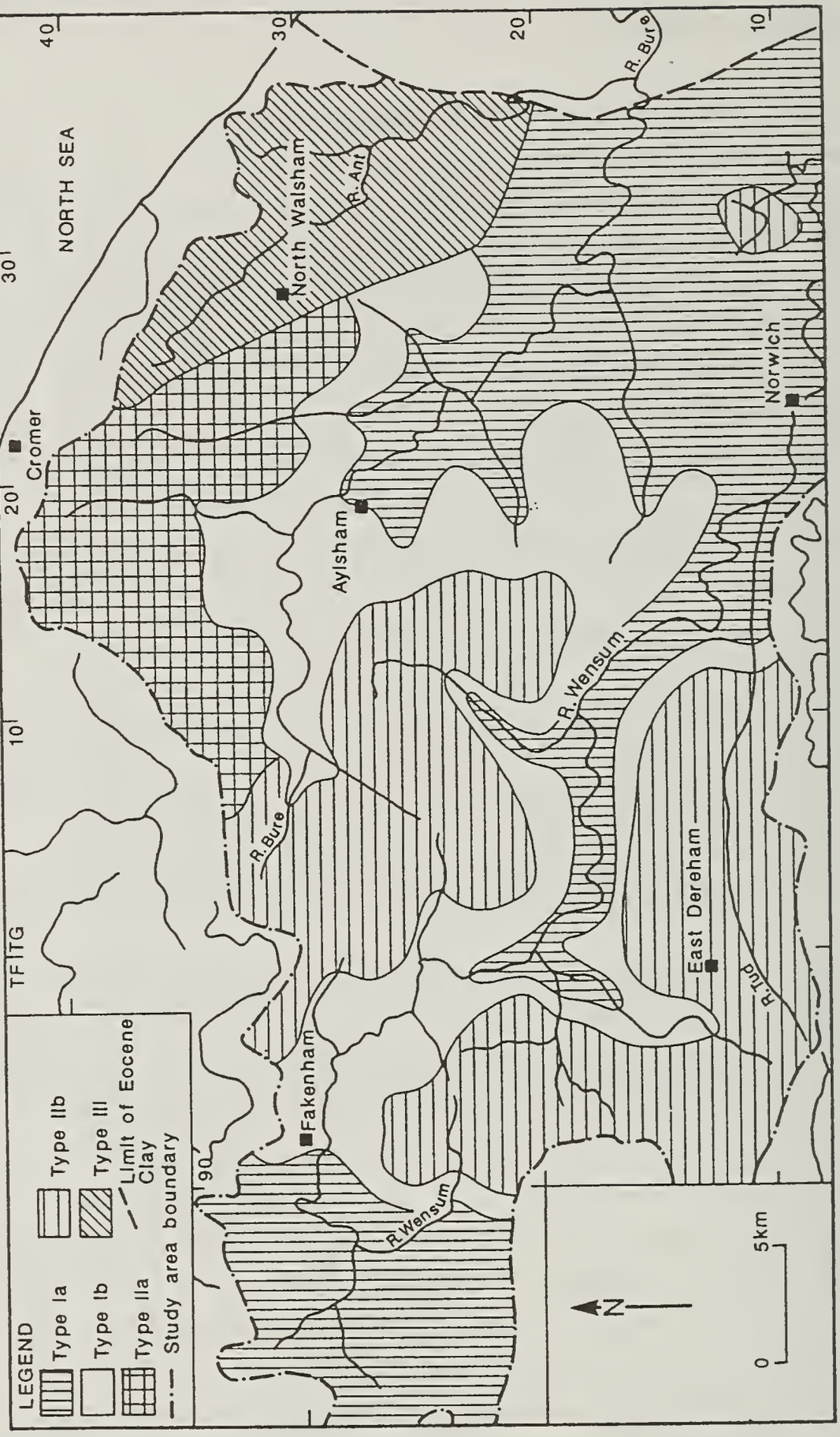

Fig.9. Distribution of Chalk groundwater hydrochemical facies present in north Norfolk.

catchment. This groundwater is characterised by low Ca (70-120 mgl^{-1}) and HCO_3 (200-300 mgl^{-1})concentrations, but is distinguished from Type Ib water by a lower SO_4 (10-50 mgl^{-1}) concentration. The NO_3 concentration is zero. The corrected carbon-14 ages for samples 1, 2 and 6 suggest that Type IIa water is of the order of 1,000 - 2,000 years old, although the presence of tritium in samples 2 and 6 (9.9 and 12.1 TU, respectively) suggests that there is a component of modern groundwater mixed in these samples.

Type IIb. This facies exists beneath the Lowestoft Till interfluvial areas of the upper Bure and Wensum catchments. Type IIb water contrasts with Type IIa in possessing a higher concentration of HCO_3 (300-400 mgl^{-1}), and detectably higher magnesium, Mg, (5-15 mgl^{-1}), and lower sodium, Na, (15-20 mgl^{-1}) concentrations. SO_4 (0 - 20 mgl^{-1}) and Cl (29 - 30 mgl^{-1}) concentrations are slightly lower than for Type IIa water. NO_3 is again undetected. The corrected carbon-14 ages for samples 11 and 12 suggest that Type IIb water may be very old, as with sample 11 (18,000 years BP), although mixing with modern water is indicated in sample 12 which has a tritium concentration of 10.1 TU and a corrected age of 1,800 years BP.

Type III. This facies occurs in the east of the area, bounded by the western limit of the Eocene Clay. The Chalk groundwater in this region of North Sea Drift cover is similar to Type IIa water in terms of the content of Ca (70-100 mgl^{-1}) and HCO_3 (200-300 mgl^{-1}). However, unlike other Chalk groundwater facies there is evidence of a saline influence in that Na (40-90 mgl^{-1}) and Cl (75-150 mgl^{-1}) concentrations are elevated. Mg (10-20 mgl^{-1}), potassium, K, (3-10 mgl^{-1}) and SO_4 (30-100 mgl^{-1}) also show elevated concentrations as the Eocene boundary is approached.

Where the aquifer is confined beneath the Eocene Clay, the chloride ion content increases where very old saline water is retained in the Chalk. There are few analyses, but the existence of a broad saline coastal zone may be assumed, with the chloride content reaching several thousand mgl^{-1}. This water shows extremely high values of non-carbonate hardness; for example, a borehole into the Chalk at Lowestoft gave a value of 2800 mgl^{-1} expressed as $CaCO_3$.

Crag facies. The Crag groundwater samples are not easily divided on the basis of hydrochemistry. Treating Crag groundwater as one hydrochemical facies, the Ca concentration ranges from 60-120 mgl^{-1} and HCO_3 from 200-350 mgl^{-1}. SO_4 concentrations are in the range 40 - 150 mgl^{-1}. Many Crag wells

are susceptible to surface contamination from agricultural sources and also from saline water ingress into the aquifer, either directly by hydraulic connection with the sea or from intrusion of tidal river water. Consequently, NO_3 (0-100 mgl^{-1}), K (5-25 mgl^{-1}), Na (20-60 mgl^{-1}) and Cl (50-120 mgl^{-1}) concentrations are variable, but generally high.

The tritium value of 12.3 TU for sample 17 suggests that this Crag water is modern, although the low value of 2.8 TU for sample 16 (Ludham Pumping Station) suggests that vertical movement of modern water may be restricted by the clay layers present in the Crag. The corrected carbon-14 age for sample 16 is 500 years BP and suggests, within the error of the age determination, that this Crag water is relatively modern, although recharged before 1954 when tritium values in rainfall first began to increase above natural levels due to thermonuclear bomb testing.

A feature of water abstracted from the Crag is its high content of Fe present as dissolved ions or colloids (Forbes, 1952; Brereton, 1978). Crag groundwater from Ludham Pumping Station has an Fe concentration of about 1 mgl^{-1}. Natural springs and seepages from the Crag are usually conspicuous by the growth of tan-coloured algae and the presence of a thin film of iron oxide on the surface of standing water. Clarke and Phillips (1984) suggest methods for treating the large amounts of Fe precipitated in pumped Crag water.

Hydrogeochemical processes

In north Norfolk, the reason for the variation in carbonate hardness of the Chalk groundwater is closely associated with the distribution and carbonate content of the glacial till deposits. In the valley zone, recharge can enter the Chalk aquifer directly, aggressively dissolving calcite in the presence of a fixed reservoir of soil CO_2. Here, Type Ia water achieves calcite saturation for PCO_2 values of between $10^{-2.2}$ - $10^{-1.7}$ bar, and compare with the range of PCO_2 values for agricultural soils in eastern England of between $10^{-1.9}$ and $10^{-1.4}$ bar,dependingon land use (Drake and Wigley, 1975; Pitman, 1978). However, Type Ib water, also located in the valley zone, has lower values of PCO_2 ($10^{-2.6}$ bar for samples 3 and 7) at calcite saturation. In areas of Type Ib water the Chalk aquifer is covered by glacial sands and gravels and Norwich Brickearth (the de-calcified member of the North Sea Drift complex) and the presence of these deposits determines that calcite equilibrium is achieved for lower values of soil PCO_2.

In the interfluvial groundwaters, recharge entering the carbonate-depleted soils developed on the North Sea Drift, in the areas of Type IIa and Type III groundwaters, attains calcite saturation for low values of soil PCO_2 in the range of $10^{-2.5}$ - $10^{-2.0}$ bar. In contrast, the carbonate-rich soils developed in the regions of Lowestoft Till permit calcite equilibrium to be achieved for higher soil PCO_2 values, in the range $10^{-2.1}$ - $10^{-2.0}$ bar.

Additionally, as shown below, pyrite oxidation and SO_4 reduction are associated with Chalk groundwater below the Lowestoft Till plateau. These processes evolve HCO_3 and, to maintain calcite equilibrium, increase the dissolved PCO_2 of Type IIb water.

A number of major and minor parameters illustrate the relationship between Chalk hydrochemistry and aquifer conditions. Mg concentrations range from 5-15 mgl^{-1} for both valley zone groundwaters (Types Ia and Ib) and interfluvial groundwaters (Types IIa and IIb). Sources of Mg, which include the clay fraction of the glacial tills, low-Mg calcite in the Chalk and montmorillonite in the non-carbonate fraction of the Chalk (Morgan-Jones, 1977), are ubiquitous in the area. Dolomite may limit Mg by solubility controls, although saturation indices for
dolomite are nearly all negative.

The increase in Mg is probably the result of exchange of Ca and Mg during long-term progressive recrystallization of microcrystalline calcite, or by incongruent dissolution of the rock carbonate, similar to the situation in the Berkshire Chalk (Edmunds et al., 1987). This process is favoured by the long groundwater residence time of Type IIb water. Only Type III water has a higher Mg concentration, and this is associated with increasing groundwater salinity as the Eocene boundary is approached.

The mean concentration of strontium (Sr) in the valley zone groundwaters (Types Ia and Ib) is 0.60 mgl^{-1} and in the interfluvial groundwaters (Types IIa and IIb) is 0.76 mgl^{-1}. The highest Sr concentrations are recorded in Type III water, with samples 18 and 20, respectively, containing 2.08 and 2.76 mgl^{-1}.

Sources of Sr include seawater, with a concentration of about 8 mgl^{-1}, and the Chalk, with a Sr content of about 500 - 800 mg kg^{-1} (Hancock, 1975). Despite the relatively low solubility of the common Sr minerals celestite ($SrSO_4$) and strontianite ($SrCO_3$), none of the Chalk groundwaters are saturated with respect to these minerals. Edmunds (1986) explains that, in low

temperature groundwaters, a high Sr/Ca ratio is probably required before strontianite can form.

Like Mg, Sr in groundwater may increase through mineral dissolution with increasing residence time, and this is evident in interfluvial Chalk groundwaters. A similar association is noticed in Chalk groundwater in south-east Suffolk (Heathcote and Lloyd, 1984). However, samples 18 and 20 (Type III) show an increase in Sr associated with increasing groundwater salinity as the Eocene boundary is approached.

Silica (SiO_2) concentrations range from 9.6 - 14.3 mgl^{-1} for the valley zone groundwaters (Types Ia and Ib) and from 11.3 - 19.7 mgl^{-1} for the interfluvial groundwaters (Types IIa and IIb). The grouping of values around 10 - 15 mgl^{-1} suggests a solubility control with an unknown silicon mineral. Sources of SiO_2 are widespread, and include the various sand formations within the glacial tills. The Chalk contains less than 0.5% SiO_2, excluding the flints (Hancock, 1975).

Controls on SiO_2 concentrations in groundwater include the neutralising effect of carbonate material in the soil zone which prevents extensive hydrolysis of silicates in recharge water, and the co-precipitation of SiO_2 with metal hydroxides as pH increases (Haines and Lloyd, 1985). In the Lincolnshire Chalk, Haines and Lloyd (1985) show that, with increasing groundwater residence time, SiO_2 concentrations increase mainly due to breakdown of the clay minerals found within the Chalk, particularly illite and montmorillonite. SiO_2 concentrations were also high in areas of old saline groundwater.

In north Norfolk, the slightly higher range of SiO_2 concentrations in interfluvial groundwaters, relative to the valley zone groundwater, also suggests an increase in SiO_2 as a result of long groundwater residence time. In the case of Type III water, the observed range of SiO_2 concentrations is from 14.6 - 22.0 mgl^{-1}, indicative of a saline influence.

The Chalk groundwater iodide (I) concentrations range from 3.8 μgl^{-1} for sample 12 (Type IIb) to 12.7 μgl^{-1} for sample 20 (Type III). Sources of iodine are various. Rainwater contains between 0.5 and 5 μgl^{-1} iodine, and seawater between 45 and 60 μgl^{-1} iodine (Whitehead, 1984). Significant amounts of iodine are present in certain marine sediments as a result of accumulation by biological processes. Chalk from Caistor quarry [TG 238 049] yielded an iodide value of 2 μgl^{-1} when crushed and shaken with distilled

water in the laboratory (Hunt, 1985). In oxidising groundwater, iodine exists mainly as iodate (IO_3), but is reduced to iodide along the groundwater flow path, the reaction coinciding with the reduction of NO_3 (Edmunds *et al.*, 1987).

The additional iodide observed in the regional Chalk groundwaters may therefore have a source in the marine clay component of the glacial tills, particularly the Lowestoft Till which incorporates marine Jurassic clays from west Norfolk and Lincolnshire. In south Lincolnshire, Jackson and Lloyd (1984) demonstrate that groundwater within sands in Devensian Till contains in excess of 50 $\mu g l^{-1}$ of iodide. In north Norfolk, only sample 10, with an iodide concentration of 12 $\mu g l^{-1}$, shows an increase that may be attributed to the presence of a thick sequence of glacial deposits, including Lowestoft Till. Type III water shows a tendency towards increased iodide concentrations (10.2 and 12.7 $\mu g l^{-1}$, respectively, for samples 19 and 20), again indicative of a saline influence.

The distributions of NO_3, SO_4 and Fe concentrations within the Chalk aquifer reflect the natural tendency towards oxygen depletion and the promotion of reducing conditions. The drift deposits are important in governing the redox conditions in the Chalk aquifer. The interfluvial groundwaters contain dissolved ferrous (Fe^{2+}) iron whereas the modern Type Ia groundwaters contain insoluble ferric (Fe^{3+}) iron.

In north Norfolk, the measured redox potential (Eh) for valley zone Type Ia water is typically, on the basis of samples 4 and 5, about 375 mV. This value represents an oxidising condition and, for this condition, NO_3 and SO_4 are present and Fe concentrations are generally less than 0.1 $mg l^{-1}$. The Eh values measured on pumped Chalk groundwater from the interfluvial areas range from 75 - 260 mV, and for this condition any NO_3 contributed by recharge has been completely reduced.

Circumstantial evidence for denitrification occurring within the glacial deposits is provided by the presence of tritium in the interfluvial groundwaters, in the absence on NO_3 (Foster et al., 1986). For example, samples 2 and 6 (Type IIa) and 12 (Type IIb) have tritium contents, respectively, of 9.9, 12.1 and 10.1 TU for zero nitrate concentrations.

The range of SO_4 concentrations for Type IIa water is from 10 - 50 $mg l^{-1}$ and for Type IIb water from 0 - 40 $mg l^{-1}$. Eastwards, SO_4 concentrations increase to between 30 - 100 $mg l^{-1}$ in Type III water, indicative ofa saline

influence. The Fe concentrations for Type IIa and IIb water vary from 0.4 - 3.7 mgl^{-1}.

Further explanation of the distribution of SO_4 and Fe in the Chalk groundwaters requires a consideration of the sources of these minerals. Sulphur containing minerals occur throughout the Chalk as nodules of marcasite and disseminated pyrite (Morgan-Jones, 1977). The mineral analyses of Perrin *et al.* (1979) show that pyrite occurs sporadically in the Lowestoft Till, probably derived from Jurassic clays to the west of the region and Chalk contained in the till. Sources of Fe include the dispersed pyrite in the Chalk and chamosite and glauconite present in both the Crag and glacial tills. Analysis of the opaque heavy minerals in the East Anglian tills showed that limonite, a widely occurring weathering product of all Fe-containing minerals, occurs in all the glacial deposits (Perrin *et al.*, 1979).

Therefore, the probable source of SO_4 and Fe in the interfluvial areas is from the oxidation of pyrite within the glacial tills, thus:

$$FeS_2 + 7/2\ O_2 + H_2O = Fe^{2+} + 2H^+ + 2SO_4^{2-} \quad (1)$$

The greatly reduced pH gives rise to increased calcite dissolution, so that a full reaction may be represented by:

$$2CaCO_3 + FeS_2 + 7/2\ O_2 + H_2O = Fe^{2+} + 2SO_4^{2-} + 2Ca^{2+} + 2HCO_3 \quad (2)$$

Chemical controls on the SO_4 produced by reaction (2) are gypsum solubility and redox reactions; although the former is discounted since none of the groundwaters are saturated with respect to gypsum. Considering the latter, under suitable reducing conditions, SO_4 will reduce to either hydrogen sulphide gas (H_2S) or to the soluble bisulphide ion (HS^-). The reduction of SO_4 to H_2S with accompanying oxidation of organic matter, as facilitated by anaerobic bacteria, can be written as:

$$SO_4^{2-} + 2CH_2O = H_2S + 2HCO_3^- \quad (3)$$

For SO_4 reduction to become quantitatively important, a long groundwater residence time is necessary (Edmunds et al., 1984).

In north Norfolk, the Type IIb groundwaters have a range of SO_4 from 4 -

44 mgl^{-1}. Inspecting the analyses of Type IIa and IIb waters, and from a theoretical consideration of reaction (2), only in sample 11, with a SO_4 concentration of 4 mgl^{-1}, is there less SO_4 than predicted on the basis of the measured Fe concentration. A similar situation occurs for samples 24 and 25 (piezometers in the Lowestoft Till) where the SO_4 concentrations are, respectively, 0 and 1 mgl^{-1}. All three samples are in the upper Bure catchment in a region of long groundwater residence time and where H_2S gas is often detected.

If it is assumed that an upper limit for SO_4 produced by pyrite oxidation in the glacial till deposits is 40 mgl^{-1}, then, in the complete reduction of SO_4 described by reaction (3), 50.8 mgl^{-1} of HCO_3 and 14.2 mgl^{-1} H_2S will be produced. The increase in HCO_3 will contribute further to the HCO_3 resulting from reaction (2). This is consistent with the observation that the HCO_3 content of Type IIb water is high, ranging from 300 - 400 mgl^{-1}. A similar situation exists for the drift groundwater samples. However, the production of a large amount of H_2S is unlikely. Some sulphide may be lost, at the low Eh encountered, through precipitation of insoluble sulphides, such as pyrite.

DISCUSSION

In north Norfolk there is an apparent conflict between the hydrogeological and hydrochemical data presented. Areas of recharge, defined by the regions of high Chalk groundwater head shown in Fig. 3, correspond with Chalk groundwater Types IIa, IIb and III which, on the basis of the corrected groundwater ages alone, have long groundwater residence times. Areas of discharge, as defined by the piezometric head distribution, coincide with the major river valleys, yet these are regions of Types Ia and Ib Chalk groundwater indicative of modern recharge.

Integrating the hydrogeological and hydrochemical data gives the interpretation of the groundwater flow mechanisms illustrated in Fig.10. In the valley zone, where the Quaternary deposits are thin or absent, recharge enters the Chalk aquifer directly. The presence of tritium and high concentrations of NO_3, SO_4 and Cl indicate a short residence time within the unconfined Chalk aquifer.

In the interfluvial areas, groundwater conditions are determined by the thickness and composition of the glacial tills overlying the Chalk. In the

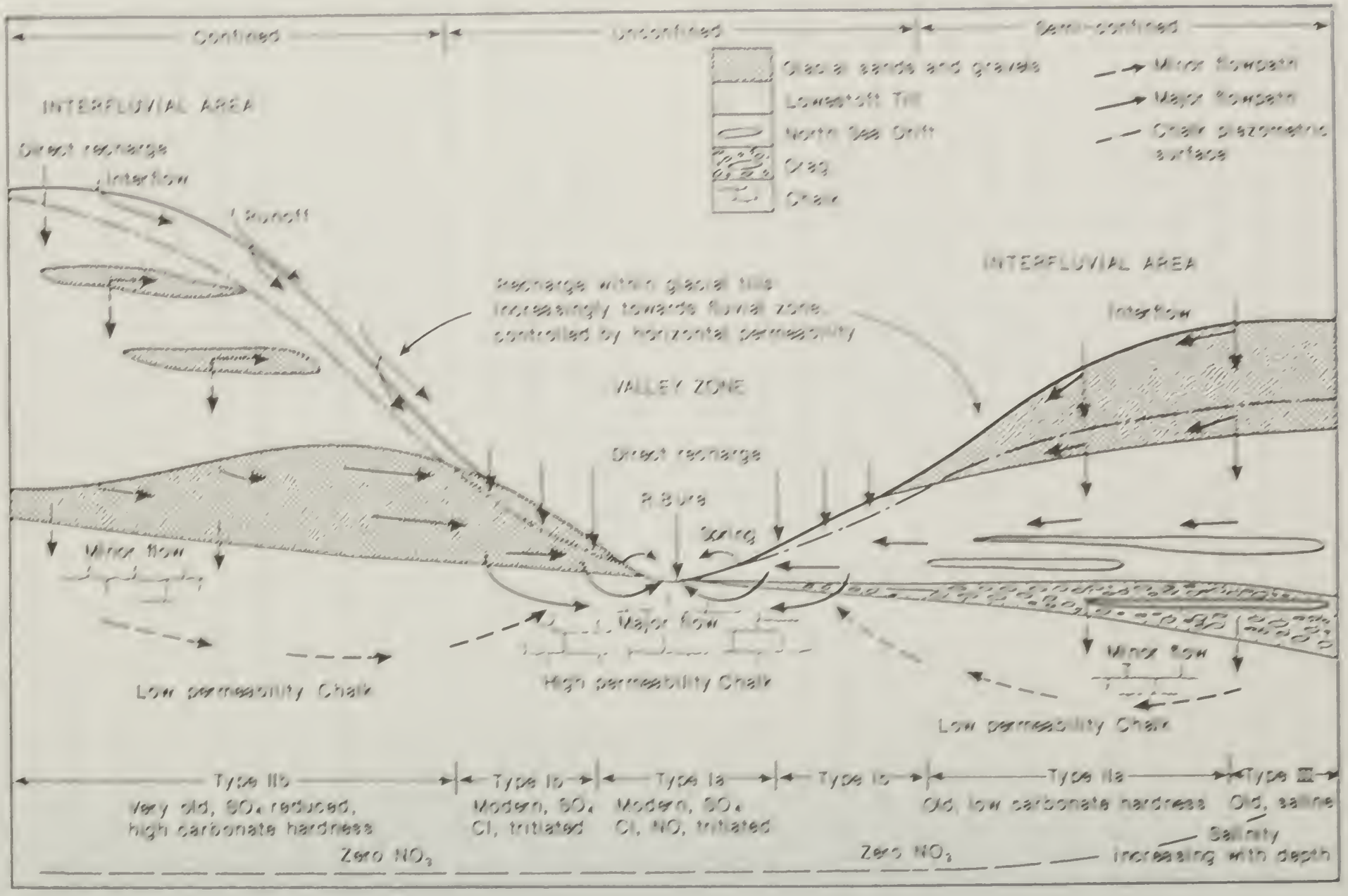

Fig.10. Schematic cross-section showing the conceptual groundwater flow mechanisms and hydrochemical variations in north Norfolk.

upper Bure catchment the thick Lowestoft Till confines the Chalk and may even cause overflowing artesian conditions. Chalk groundwater can be very old, as much as 18,000 years BP, and may represent recharge that entered the aquifer before the last Devensian ice advance.

In areas covered by North Sea Drift, where the relatively higher percentage sand content of this till permits greater recharge, the maximum age of Type IIa Chalk groundwater is of the order of 1,000 - 2,000 years BP.

In the interfluvial areas, the long groundwater residence time and minimal vertical recharge through the glacial tills promote reducing conditions and the progressive removal of NO_3 and SO_4, together with an increase in the dissolved Fe content. Prolonged contact with the Lowestoft Till produces a small increase in the Na and iodide content of the underlying Type IIb Chalk water. Mg, Sr and SiO_2 also have the opportunity to increase through long contact with the Chalk by theprocessesof incongruent dissolution of calcite and breakdown of clay minerals.

The chemistry of Type III water, with increasing concentrations of Na, Mg, Sr, SiO_2, Cl and iodide, indicates a saline influence as the Eocene boundary is approached. The view of Bath and Edmunds (1981) working at Trunch, within the area of Type III water, in accounting for all or part of the Sr enrichment, is to suggest that the fissure-derived water is within the mixing series between connate interstitial water and infiltrating meteoric water. This view is supported by the corresponding Cl concentrations (57 - 69 mgl^{-1}) which are in excess of values predicted for infiltration of local rainfall, concentrated by evapotranspiration.

The proximity of Trunch to the old saline Chalk groundwater trapped below the Eocene strata supports the view of Bath and Edmunds (1981), but it is difficult to reconcile this with the known geological history of the area which suggests that complete flushing of formation water from the effective Chalk aquifer must have occurred prior to the transgression of seawater into the area at the start of the Pleistocene, 1.6×10^6 years BP. It is possible that the present salinity in the effective Chalk aquifer represents a Pleistocene Crag seawater influence, particularly since such a saline influence is not observed in the west of the study area where Pleistocene Crag is absent.

Towards the fluvial margins, the glacial deposits thin and the percentage of sands and gravels contained in the deposits, particularly in the

west of the area, increases. Associated with this change, the concentrations of SO_4 and Cl begin to increase and tritium is detected in the groundwater. These observations are evidence for lateral movement of recharge occurring through thin, permeable zones within the glacial deposits. The recharge is progressively transferred to the fluvial margin where it enters a zone of major groundwater flow within a region of high chalk transmissivity.

At the fluvial margin, storage and release of water is controlled by the mass of sands and gravels within the glacial deposits. A lumped parameter model calibrated by De Silva (1984) to represent the unconfined and confined components of the Bure catchment downstream to Wroxham, for the period 1975-1982, yielded unconfined and semi-confined storage values of 0.11 and 0.02, respectively. The model results demonstrate the importance of the sands and gravels in increasing the storage of the Chalk aquifer system, particularly in the unconfined areas. Significantly, the model only gave satisfactory results after recharge had been routed via linear reservoirs, demonstrating a possible delay in recharge entering the Chalk aquifer through the glacial tills.

Occasionally, anomalously high Fe concentrations are encountered at the fluvial margin where the edge of the Lowestoft Till plateau is encountered. Sample 3 (Type Ib water) is an example with an Fe concentration of 9.9 mgl^{-1} and an Eh of 55 mV. The chemically reduced nature of this sample in association with a tritium content of 4.2 TU suggests that this is a mixed groundwater. The Pleistocene deposits at deposits at this site are 23.8 m thick and are highly ferruginous with iron oxides coating the surfaces of quartz grains. Therefore, the likely cause of the high Fe concentration is the mixing of a modern oxygenated recharge water at the fluvial margin with a reduced regional groundwater emerging at the edge of the Lowestoft Till plateau. The change from an oxidising to a reducing environment within the Fe-rich Pleistocene deposits possibly promotes further dissolution of Fe with a source in the local Pleistocene deposits.

Song and Atkinson (1985) report a similar situation for Type Ib water in a Chalk borehole at Corpusty in the upper Bure area. Here, a thick gelatinous suspension of filamentous bacteria with attached iron oxy-hydroxide was found in the middle section of the water column, apparently thriving where oxygenated recharge water mixes with a reduced, Fe-rich water of regional origin.

CONCLUSIONS

In north Norfolk, the hydrogeology and hydrochemistry of the Chalk aquifer system are closely associated with the distribution of clay-rich Lowestoft Till and sandy North Sea Drift deposits. The carbonate content of the glacial deposits influence significantly the alkalinity of the recharge water. Chalk groundwaters beneath deposits of Lowestoft Till and North Sea Drift can be separated by a HCO_3 concentration of 300 mgl^{-1}, with values in excess of this concentration associated with the carbonate-rich Lowestoft Till plateau. The long groundwater residence time of interfluvial groundwater promotes incongruent dissolution of calcite and redox reactions within both the drift and the Chalk groundwaters.

Combining the hydraulic and hydrochemical evidence leads to the conclusion that the glacial deposits are important in controlling recharge and groundwater flow within the aquifer system. The glacial till covered interfluve regions inhibit direct recharge to the Chalk, although the tritium data provide evidence for a small component of recharge through more permeable material within the bulk of the till. As the valley zone is approached, an increasing amount of recharge is transferred to the aquifer through the glacial deposits. At the fluvial margin, storage and release of recharge to the high region of chalk transmissivity in the valley zone is controlled by deposits of glacial sands and gravels. In the Bure catchment, groundwater storage is particularly important given the predominance of sandy North Sea Drift.

This work illustrates the requirement to integrate hydraulic and hydrochemical evidence in order to provide a correct assessment of available groundwater resources and the potential for groundwater pollution. In north Norfolk, good quality water and a zero nitrate content exists beneath the interfluvial areas, but borehole yields are poor as a result of low chalk transmissivity. In contrast, better yields associated with high chalk transmissivity in the valley zone are prone to contamination, mainly from agricultural sources. For the future, the fluvial margin may offer a suitable location for development, since reasonable yields and good quality water, possibly maintained by denitrification, are obtainable; although the occasional high Fe concentration may be encountered.

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REFERENCES

Atkinson, T.C, 1981. *Report on subsidences at Saxthorpe, Norfolk in January 1979.* Unpubl. Rep., 15 pp.

Baden-Powell, D.F.W., 1948. The Chalky Boulder Clays of Norfolk and Suffolk. *Geol. Mag.*, 85: 279-296.

Back, W., 1961. Techniques for mapping hydrochemical facies. *U.S. Geol. Surv. Prof. Paper* 498-A 42 pp.

Baker, H.A., 1918. On successive stages in the denudation of Chalk in East Anglia. *Geol. Mag.*, 55: 412-416.

Banham, P.H., 1968. A preliminary note on the Pleistocene stratigraphy of north-east Norfolk. *Proc. Geol. Assoc.*, 79: 507-512.

Banham, P.H., 1975. Glacitectonic structures: a general discussion with particular reference to the contorted drift of Norfolk. In: A.E. Wright and F. Moseley (Editors) *Ice Ages: ancient and modern. Geol. J. Special Issue* No.6: 69-94.

Banham, P.H., Davies, H. and Perrin, R.M.S., 1975. Short field meeting in north Norfolk. *Proc. Geol. Assoc.*, 86: 251-258.

Bath, A.H. and Edmunds, W.M., 1981. Identification of connate water in interstitial solution of Chalk sediment. *Geochim. Cosmochim. Acta*, 45: 1449-1461.

Bishop, P.K. and Lloyd, J.W., 1991. Use of ^{14}C modelling to determine vulnerability and pollution of a carbonate aquifer: the Lincolnshire Limestone, eastern England. *Applied Geochem.*, 6: 319-331.

Boulton, G.S., Cox, F.C., Hart, J. and Thornton, M., 1984. The glacial geology of Norfolk. *Bull. Geol. Soc. Norf.*, 34: 103-122.

Brereton, N.R., 1978. *The effects of iron bacteria on the yield and efficiency of groundwater supply boreholes.* Water Research Centre Report LR895, 14pp.

Catt, J.A., Corbett, W.M., Hodge, C.A.H., Madgett, P.A., Tatler, W. and Weir, A.H., 1971. Loess in the soils of north Norfolk. *J. Soil Sci.*, 22: 444-452.

Clarke, K.B. and Phillips, J.H., 1984. Experiences in the use of East Anglian sands and gravels ('Crags') as a source of water supply. *J. Instn. Water Eng. Sci.*, 38: 543-549.

Cox, F.C. and Nickless, E.F.P., 1972. Some aspects of the glacial history of Central Norfolk. *Bull. Geol. Surv. G.B.*, 42: 79-98.

De Silva, K.S.R., 1984. *Lumped parameter groundwater model for the River Bure catchment, Norfolk.* Unpubl. MSc Thesis, Univ. of Birmingham, 73 pp.

Downing, R.A., 1966. *Hydrogeology of northern East Anglia with special reference to the Chalk.* Unpubl. Institute of Geological Sciences Report.

Downing, R.A., Edmunds, W.M. and Gale, I.N., 1987. Regional groundwater flow in sedimentary basins in the U.K. In: J.C. Goff and B.P.J. Williams (Editors), *Fluid flow in sedimentary basins and aquifers.* Geol. Soc. Special Publ. No. 34. Blackwell Scientific Publications, Oxford, pp. 105-125.

Drake, J.J. and Wigley, T.M.L., 1975. The effect of climate on the chemistry of carbonate groundwater. *Water Resour. Res.*, 11: 958-962.

East Suffolk and Norfolk River Authority, 1971. First Survey of resources and demands. East Suffolk and Norfolk River Authority, 126 pp.

Edmunds, W.M., 1986. Groundwater chemistry. In: Brandon, T.W. (Editor), *Groundwater: occurrence, development and protection.* Water Practice Manual 5, The Institution of Water Engineers and Scientists, London, pp 49-107.

Edmunds, W.M., Cook, J.M., Darling, W.G., Kinniburgh, D.G., Miles, D.L., Bath, A.H., Morgan-Jones, M. and Andrews, J.N., 1987. Baseline geochemical conditions in the Chalk aquifer, Berkshire, U.K.: a basis for groundwater quality management. *Applied Geochem.*, 2: 251-274.

Edmunds, W.M., Miles, D.L. and Cook, J.M., 1984. A comparative study of sequential redox processes in three British aquifers. In: E. Eriksson (Editor), *Hydrochemical balance of freshwater systems*. Prof. Int. Assoc. Hydrol. Sci., 59: 55-70.

Forbes, C.L., 1952. Ludham borehole: a gravel pack well in the Norwich Crag. *J. Instn. Water Eng. Sci.*, 6: 362-369.

Foster, S.S.D., Bridge, L.R., Greake, A.K., Lawrence, A.R. and Parker, J.M. 1986. The groundwater nitrate problem: a summary of research on the impact of agricultural land-use practices on groundwater quality between 1976 and 1985. *Hydrogeol. Rep. Br. Geol. Surv.*, No. 86/2.

Foster, S.S.D, and Robertson, A.S., 1977. Evaluation of a semi-confined Chalk aquifer in East Anglia. *Proc. Inst. Civ. Engrs.*, 63: 803-817.

Funnell, B.M., 1961. The Palaeogene and Early Pleistocene of Norfolk. *Trans. Norfolk Norwich Nat. Soc.*, 19: 340-364.

Funnell, B.M., Norton, P.E.P. and West, R.G., 1979. The Crag at Bramerton, near Norwich, Norfolk. *Phil. Trans. Roy. Soc. Lond.*, 287B: 489-534.

Funnell, B.M. and West, R.G., 1977. Preglacial Pleistocene deposits of East Anglia. In: F.W. Shotton (Editor), *Brit. Quat. Studies - Recent Advances*. Oxford Univ. Press, pp 247-65.

Haines, T.S. and Lloyd, J.W., 1985. Controls on silica in groundwater environments in the United Kingdon. *J. Hydrol.*, 81: 277-295.

Hancock, J.M., 1975. The petrology of the Chalk. *Proc. Geol. Assoc.*, 86: 499-535.

Hart, J.K., Hindmarsh, R.C.A. and Boulton, G.S., 1990. Styles of subglacial glaciotectonic deformation within the context of the Anglian ice-sheet. *Earth Surf. Processes and Landforms*, 15: 227-241.

Headworth, H.G., Keating, T. and Packman, M.J., 1982. Evidence for a shallow highly-permeable zone in the Chalk of Hampshire, *U.K. J. Hydrol.*, 55: 93-112.

Heathcote, J.A. and Lloyd, J.W., 1984. Groundwater chemistry in southeast Suffolk (U.K.) and its relation to Quaternary geology. *J. Hydrol.*, 75: 143-165.

Hopson, P.M., 1984. The Pleistocene in three dimensions: Beccles to Lowestoft. *Proc. of the Brit. Association for the Advancement of Science*, Norwich, 1984.

Hunt, R.C., 1985. *An investigation of iodide concentrations in fresh groundwaters in Chalk aquifers of the U.K.* Unpubl. MSc Thesis, Univ. of Birmingham, 79 pp.

Ineson, J., 1962. A hydrogeological study of the permeability of the Chalk. *J. Instn. Water Eng. Sci.* 16: 449-463.

Ineson, J and Downing, R.A., 1963. Changes in thechemistry of groundwaters of the Chalk passing beneath argillaceous strata. *Bull. Geol. Surv. G.B.*, 20: 176-192.

Institute of Geological Sciences, 1968. Records of wells in the area of new Series One-Inch (Geological) Aylsham (147) sheet. Well Catalogue Series. Natural Environment Research Council, London, 121pp.

Institute of Geological Sciences, 1976. 1:125,000 Hydrogeological map of northern East Anglia. Sheet 1: Regional hydrological characteristics and explanatory notes. IGS, DoE.

Jackson, D. and Lloyd, J.W., 1984. An integrated hydrochemical approach to deduce the response of an aquifer system during its history of abstraction. *Ground Water*, 22: 735-745.

Kazi, A. and Knill, J., 1969. The sedimentation and geotechnical properties of the Cromer Till between Happisburgh and Cromer, Norfolk. *Q.J.eng. Geol. Lond.*, 2: 63-86.

Krinsley, D.H. and Funnell, B.M.,. 1965. Environmental history of quartz sand grains from the Lower and Middle Pleistocene of Norfolk, England. *Q.J. Geol. Soc. Lond.*, 124: 435-461.

Lloyd, J.W., Harker, D. and Baxendale, R.A., 1981. Recharge mechanisms and groundwater flow in the Chalk and drift deposits of southern East Anglia. *Q. J. eng. Geol. Lond.*, 14: 87-96.

Lloyd, J.W. and Heathcote, J.A., 1985. *Natural inorganic hydrochemistry in relation to groundwater: an introduction.* Clarendon Press, 296 pp.

Morgan-Jones, M., 1977. Mineralogy of the non-carbonate material from the Chalk of Berkshire and Oxfordshire, England. *Clay Minerals*, 12: 331-334.

Otlet, R.L., 1977. *Isotope measurements for hydrological investigations.* Low level measurements laboratory, Harwell, 8pp.

Peake, N.B. and Hancock, J.M., 1961. The Upper Cretaceous of Norfolk. *Trans. Norfolk Norwich Nat. Soc.*, 19: 293-339.

Perrin, R.M.S., Rose, J. and Davies, H., 1979. The distribution, variation and origins of Pre-Devensian Tills in eastern England. *Phil. Trans. Roy. Soc. Lond.*, 287B: 535-570.

Pitman, J.I., 1978. Carbonate chemistry of groundwater from Chalk, Givendale, east Yorkshire. *Geochim. Cosmochim. Acta*, 42: 1885-1897.

Price,M., 1987. Fluid flow in the Chalk of England. In: J.C.Goff and B.P.J. Williams (Editors), *Fluid flow in sedimentary basins and aquifers.* Geol. Soc. Special Publ. No. 34. Blackwell Scientific Publications, Oxford, pp.141-156.

Rawson, P.F., Curry, D., Dilley, F.C., Hancock, J.M., Kennedy, W.J., Neale, J.W., Wood, C.J. and Worssam, B.C., 1978. A correlation of Cretaceous rocks in the British Isles. *Geol. Soc. Special Publ.* No. 9, 70pp.

Reid, C., 1882. The geology of the country around Cromer. *Mem. Geol. Surv.*, U.K.

Rodda, J.C., Downing, R.A. and Law, F.M., 1976. *Systematic Hydrology.* Newnes-Butterworths, London, 399 pp.

Sharp, J.M., 1984. Hydrogeologic characteristics of shallow drift aquifers in dissected till planes (North-Central Missouri). *Ground Water*, 22: 683-689.

Shotton, F.W., Banham, P.H. and Bishop, W.M., 1977. Glacial-interglacial stratigraphy of the Quaternary in Midland and eastern England. In: F.W. Shotton (Editor) *Brit. Quat. Studies - Recent Advances.* Oxford Univ. Press, pp. 247-265.

Soloman, J.D., 1932. The glacial succession on the north Norfolk coast. *Proc. Geol. Assoc.*, 43: 241-271.

Song Lin-Hua and Atkinson, T.C., 1985. Dissolved iron in chalk groundwaters from Norfolk, England. *Q.J. eng. Geol. Lond.*, 18: 261-274.

Song Lin-Hua and Atkinson, T.C., 1991. Chemical reaction between concrete and natural groundwaters and its implications for the commissioning of observation boreholes in chalk. *Q.J. eng. Geol. Lond.*, 24: 221-229.

Stiff, H.A., 1951. The interpretation of chemical water analysis by means of patterns. *J. Petrol. Technol.*, 3: 15-17.

Straw, A., 1979. Eastern England. In: A. Straw and K.M. Clayton, *The Geomorphology of the British Isles*. Methuen, London, 247pp.

Toynton, R., 1979. *Waste disposal hydrogeology with special reference to the Chalk of East Anglia*. Unpubl. PhD. Thesis, University of East Anglia.

Toynton, R., 1983. The relation between fracture patterns and hydraulic anisotropy in the Norfolk Chalk, England. *Q.J. eng. Geol. Lond.*, 16: 169-185.

West, R.G., 1980. *The Preglacial Pleistocene of the Norfolk and Suffolk Coasts*. Cambridge University Press, Cambridge.

West, R.G. and Donner, J.J., 1956. The glaciations of East Anglia and the East Midlands, a differentiation based on stone orientation measurements of the tills. *Q.J. Geol. Soc. Lond.*, 112: 69-91.

Williams, R.B.G., 1969. Permafrost and temperature conditions in England during the last glacial period. In: T.L. Pieve (Editor), *The periglacial environment*. McGill- Queens University Press, Montreal, pp. 339-410.

Whitehead, D.C., 1984. The distribution and transformations of iodine in the environment. *Environ. Int.*, 10: 321-339.

Wood, S.V. and Harmer, F.W., 1868. The glacial and post-glacial structure of Norfolk and Suffolk. *Geol. mag.*, 5: 452-456.

Woodland, A.W., 1946. *Water supply from underground sources of Cambridge-Ipswich district*. Wartime Pamphlet No. 20 pt. 10, Geol. Surv. Gt. Brit., 88.

Woodland, A.W., 1970. The buried tunnel-valleys of East Anglia. *Proc. Yorks. Geol. Soc.*, 37: 521-578.

RADIOLARIA FROM THE MELBOURN ROCK OF EAST ANGLIA

Simon K. Haslett

School of Environmental Sciences,
University of East Anglia,
Norwich, NR4 7TJ.

ABSTRACT

A meagre radiolarian assemblage was collected from the Melbourn Rock of East Anglia. The specimens examined had not been replaced by calcite and constitute the first record of siliceous radiolaria from the British Chalk (other than in flint-meal). Although the biostratigraphic information that such a restricted fauna can yield is limited, the presence of *Novixitus mclaughlini* Pessagno constrains the age of the sample to within the Cenomanian.

INTRODUCTION

Radiolaria are protists that secrete a siliceous test, are wholly marine and possess a geological record extending back to the Cambrian. Very few studies have been made on British radiolaria, primarily because of their rarity and also because where they do occur it is usually within a siliceous lithology such as chert, from which it is extremely difficult to extract them. In the Cretaceous of Britain they are commonest in the Chalk (Hill & Jukes-Brown, 1895; Murton-Holmes, 1900), although they have been recovered from the Greensand (Grimes, 1895).

The study of radiolaria in these rocks is hindered by the replacement of the original siliceous radiolarian test by calcite. Where this has occurred radiolaria have traditionally been examined in thin-section (Hill & Jukes-Brown, 1895), however it would also be possible to process the chalk as for the extraction of foraminifera, and to pick out the radiolarians individually. Radiolaria have been recovered in their original siliceous form from the interior of flints from the Chalk (Murton-Holmes, 1900), but not previously from the Chalk itself.

It is the aim of this study to describe a meagre occurrence of

radiolaria from the Melbourn Rock, that have not been replaced by calcite. Radiolaria have previously been described from the Melbourn Rock (Hill & Jukes-Brown, 1895) and Chalk Marl (Hill, 1912) of Norfolk, Hertfordshire, Lincolnshire and Yorkshire. However, in all these occurrences the radiolaria described have been replaced by calcite.

MATERIAL AND METHODS

The sample was collected from a road cutting on the A505 through the Melbourn Rock at Hyde Hill, east of Royston, Hertfordshire (TL 373408). Radiolaria were detected in the field using methods described by Haslett & Robinson (1991). The sample was processed by disaggregating 1Kg of Chalk using a pestle and mortar. The sample was then put into a large glass beaker and dilute Hydrochloric acid was added to dissolve all Calcium Carbonate; this was continued until the reaction ceased. The insoluble residue was then washed through a 63μm sieve to remove the clay-sized fraction. Ten strewn slides were prepared from the >63μm insoluble residue and mounted in Canada Balsam. Four specimens were found and are described here.

SYSTEMATIC PALAEONTOLOGY

Subclass RADIOLARIA Muller

Superorder POLYCYSTINA Ehrenberg

Order NASSELLARIA Ehrenberg

Family PSEUDODICTYOMITRA Pessagno

Genus *Novixitus* Pessagno

Novixitus mclaughlini Pessagno

Fig. 1a.

1977 *Novixitus mclaughlini* Pessagno, p. 54, pl. 9, fig. 17.
1981 *Novixitus mclaughlini* Pessagno; De Wever & Thiebault, p. 589, pl. 2, fig. 3.
1988 *Novixitus mclaughlini* Pessagno; Thurow, p. 402, pl. 3, fig. 21.
1991 *Novixitus mclaughlini* Pessagno; Passerini *et al.*, fig. 3f, g.

Material: One well preserved specimen.

Description: Conical outline, seven segmented with two rows of large tubercles on the first and second post-abdominal segments, and small tubercles on the third and fourth post-abdominal segments. Chambers regularly increase in size distally, as does the size of the pores, which are arranged in 2-4 transverse

rows per segment.

Remarks: This species has a stratigraphic range extending from the Albian in the Atlantic (Thurow, 1988) to the Cenomanian-Turonian boundary, where it becomes extinct (Passerini, *et al.*, 1991).

Order SPUMELLARIA Ehrenberg

Gen. et sp. indet.

Figs. 1b, c.

Material: Two poorly preserved specimens.

Description: Spicular form with six horny spines occurring perpendicular to one another. The structure is reinforced with lateral bars near the central attachment, which joins all adjacent spines together. This network of bars produces eight triangular windows or pores.

Remarks: The author was unable to find any similar form in Cretaceous radiolarian literature, although it does have a superficial resemblance to the Cenozoic genus *Anomalacantha* Loeblich & Tappan.

Incertae sedis

Gen. et sp. indet.

Fig. 1d.

Material: One poorly preserved specimen.

Description: A single inclined siliceous band with one perimeter possessing a smaller diameter than the other. The band is divided into three by what appear to be sutures. The first, closest to the inner perimeter, possesses a single row of circular pores; the second is ornamented with furrows in which lie oval pores; the third comprises numerous plates (?), each of which is rounded producing a 'frilly', incised appearance to the outer perimeter.

Remarks: This specimen may in fact represent a detached segment of a Nassellarian.

DISCUSSION

Although this study was limited, it is encouraging because it is very likely that there were more than four specimens of radiolaria in the 1Kg of Chalk processed. However, other specimens had probably been replaced by calcite and so were lost in the Hydrochloric acid treatment. It is worthwhile in pursuing

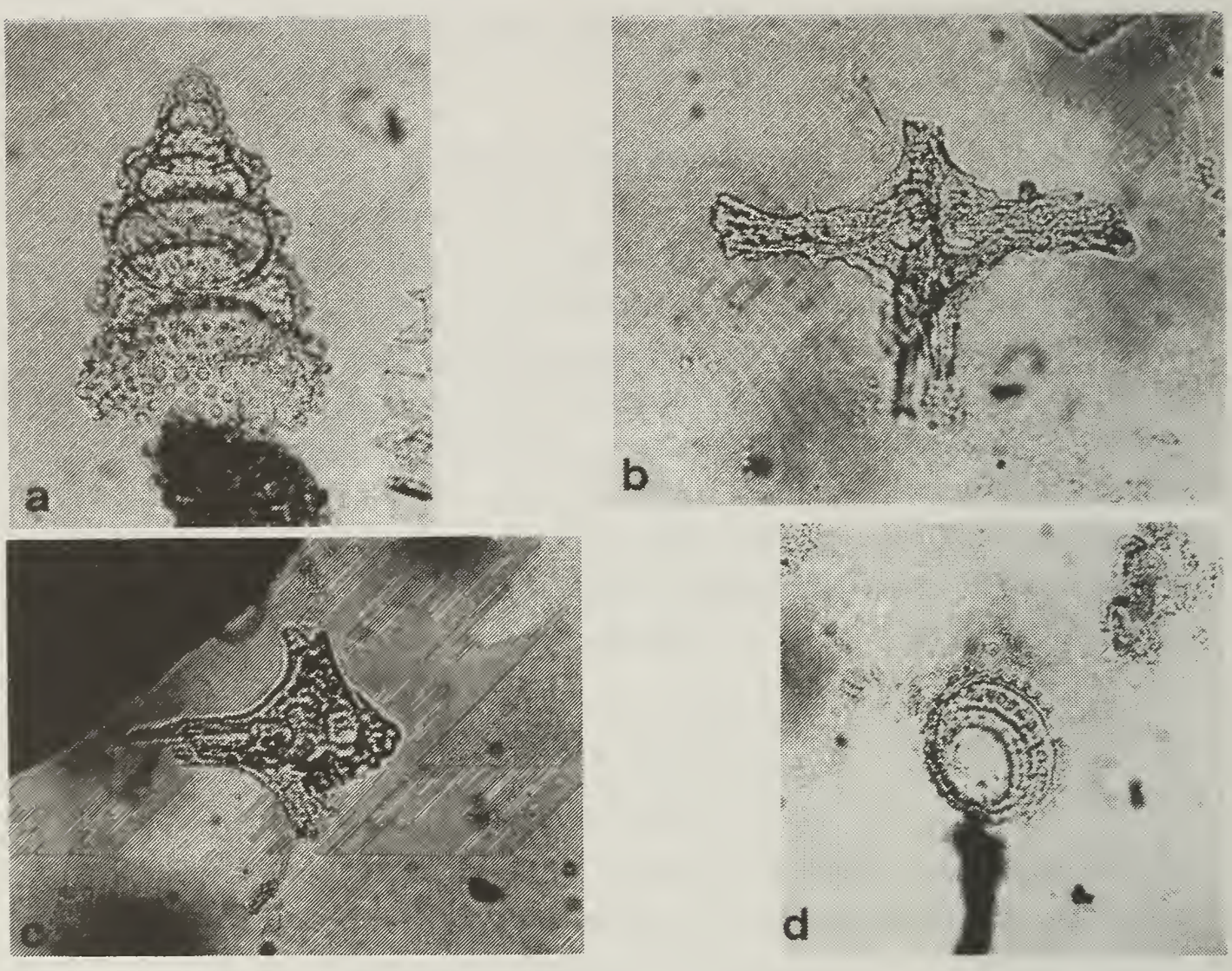

Fig. 1. a) *Novixitus mclaughlini* Pessagno (x315); b) Spumellarian Gen. et sp. indet. (x550); c) Spumellarian Gen. et sp. indet. (x500); d) *Incertae sedis* Gen. et sp. indet. (x240).

the study of radiolaria in the British Cretaceous, whether replaced by calcite or not, because of the useful biostratigraphic information that can be gained. For example, in this restricted study, the presence of a single specimen of *Novixitus mclaughlini* Pessagno dates the sample of Melbourn Rock below the Cenomanian-Turonian boundary, which the Melbourn Rock is thought to represent. Therefore, this sample is very probably of Cenomanian age.

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REFERENCES

De WEVER, P., & THIEBAULT, F., 1981. Les radiolaires d'age Jurassique superieur a Cretace superieur dans les radiolarites du Pinde - Olonos (presqu'ile de Koroni, Peloponnese meridional, Grece). *Geobios*, **14**, 577-609.

GRIMES, G. E., 1895. Two occurrences of radiolarians in English Cretaceous rocks. *Geological Magazine*, **32**, 345-347.

HASLETT, S. K., & ROBINSON, P. D., 1991. Detecting radiolaria in the field. *Journal of Micropalaeontology*, **10**, 22.

HILL, W., 1912. Rocks containing radiolaria. *Proceedings of the Geologists' Association*, **23**, 62-91.

HILL, W., & JUKES-BROWN, A. J., 1895. On the occurrence of radiolaria in the Chalk. *Quarterly Journal of the Geological Society of London*, **51**, 601-608.

MURTON-HOLMES, W., 1900. On radiolaria from the Upper Chalk at Coulsdon (Surrey). *Quarterly Journal of the Geological Society of London*, **54**, 694-704.

PASSERINI, M. M., BETTINI, P., DAINELLI, J., & SIRUGO, A., 1991. The "Bonarelli Horizon" in the central Apennines (Italy): radiolarian biostratigraphy. *Cretaceous Research*, **12**, 321-331.

PESSAGNO, E. A. Jr., 1977. Lower Cretaceous radiolarian biostratigraphy of the Great Valley Sequence and Franciscan Complex, California Coast Ranges. *Cushman Foundation for Foraminiferal Research, Special Publication*, **15**, 87pp.

THUROW, J., 1988. Cretaceous radiolarians of the North Atlantic Ocean: ODP Leg 103 (Sites 638, 640, & 641) and DSDP Legs 93 (Site 603) and 47B (Site 398). *Proceedings of the Ocean Drilling Project, Scientific Results*, **103**, 379-418.

NOTE ADDED IN PROOF

Since this note was written the author has become aware that the two Spumellaria Gen. et sp. indet. specimens may in fact be siliceous spicules of the sponge *Ventraculites*.

THE PHRAGMACONE OF *Belemnitella* cf. *langei* JELETZKY, 1948

Paul S. Whittlesea

8 Eaton Old Hall
Hurd Road
Norwich, NR4 7BE

ABSTRACT

Recent collecting has produced the first recorded specimens of the phragmacone belonging to the belemnite *Belemnitella* cf. *langei* Jeletzky, 1948 preserving the connecting rings and septa, including segments inferred to have come from beneath the proostracum. The structure of the phragmacone is described and significant features compared with those of selected Mesozoic belemnites.

INTRODUCTION

Belemnites are common fossils with a wide geographical distribution. Their nektonic lifestyle meant that their distribution was largely unaffected by facies changes that greatly influenced contemporary benthic communities. As a result, they have long been important in Upper Cretaceous stratigraphy.

In assessing the relative taxonomic value of coleoid morphological features, Jeletzky (1966) assigned the greatest importance to the proostracum, writing that "without it no comparison [of the shells of coleoid taxa] would be possible", and went on to comment that its value had long been underrated. Of the phragmacone, ranked next in importance, he wrote "The structure of the septal necks of belemnite-like coleoids... is another morphological feature that has been neglected.", and "Generally speaking, it is just as significant taxonomically as the proostracum...".

Part of the reason for the neglect these features have suffered arises from a purely practical consideration: only the strongly calcified guard is ever commonly found.

During the summer of 1991, a search of chalk dumped at a site near the

Norfolk showground at Marlingford (TG 157 096) produced a considerable quantity of material, including many belemnite guards. The chalk is believed to have been excavated from Caistor St. Edmund chalk pit, (TG 238 046), which exposes chalk belonging to the lower and middle part of the Beeston Chalk division of the Upper Campanian zone of *Belemnitella mucronata* sensu lato.

The alveoli of these belemnites were cleaned of chalk prior to examining them for cryptic species of bryozoa. During the preparation of one of these the end of a brown, chitinous-looking, tubular structure was noticed adjacent to the ventral surface. Subsequent careful excavation freed a 5mm long ringed structure which was identified as being the remains of the phragmacone, primarily some connecting rings with broken adherent septa. At this stage the guard was carefully split lengthways to reveal the adapical region of the phragmacone in situ (including the terminal membrane and pro-septum) exhibiting complete septa and connecting rings (though the shock of splitting the guard caused it to rotate through 90 degrees).

The phragmacone was then photographed in order to provide "working drawings". It had been intended to make use of scanning electron microscopy (SEM) to provide definitive illustrations; regretably, most of this tiny, feather-light structure blew out of position and had consequently to be cemented to a glass slide for safe-keeping where further observations and measurements were made.

Subsequent to this, a systematic search of all the other belemnite guards found was undertaken which produced a further useful specimen that preserved a 23mm section of seven fused connection rings lacking septa.

MATERIAL

Specimen 1, author's catalogue number MFD(S1)21/1. The specimen preserved portions of the phragmacone in two regions. The first was at the adapical end of the alveolar cavity (and included the protoconch); it contained a 3mm portion of the phragmacone showing fused connecting rings and septa (now mounted on a glass slide). This area was bounded towards the anterior by a compacted mass of fragmented, isolated septa and some phosphatic chalk. The second region was the ventral floor of the adoral end of the alveolus (15mm from the protoconch), that

yielded a 5mm fragment of the phragmacone infilled with soft white chalk.

Specimen 2, BM(NH) catalogue number C59589. This specimen preserves a 23mm section of the phragmacone showing seven united connecting rings without septa from a position inferred to have been adoral of the guard, probably beneath the proostracum. It lays embedded in the phosphatic chalk plug of the alveolus close to the dorsal margin.

Both specimens are guards of *Belemnitella* cf. *langei* that have been truncated just adapical of the protoconch and split in the ventro-dorsal plane to reveal the alveolus.

DESCRIPTION

The following description of the specimens is based upon observations made using optical microscopy and examination of ordinary light and SEM photographs of the specimens. No sections of any of the specimens were made owing to the scarcity and extreme fragility of the material. Consequently, no details can be given of the internal structure of individual components of the phragmacone, and some of the dimensions of significant structures could not be ascertained satisfactorily.

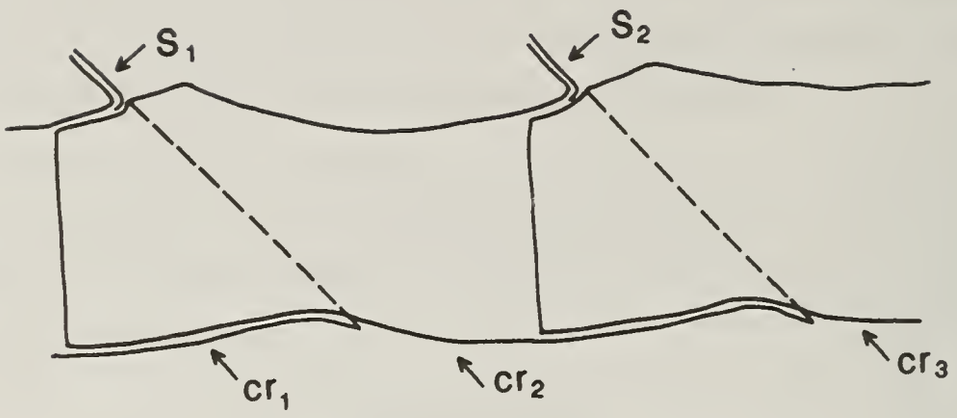
Connecting rings

0 - 4mm from the adapical end of the protoconch.

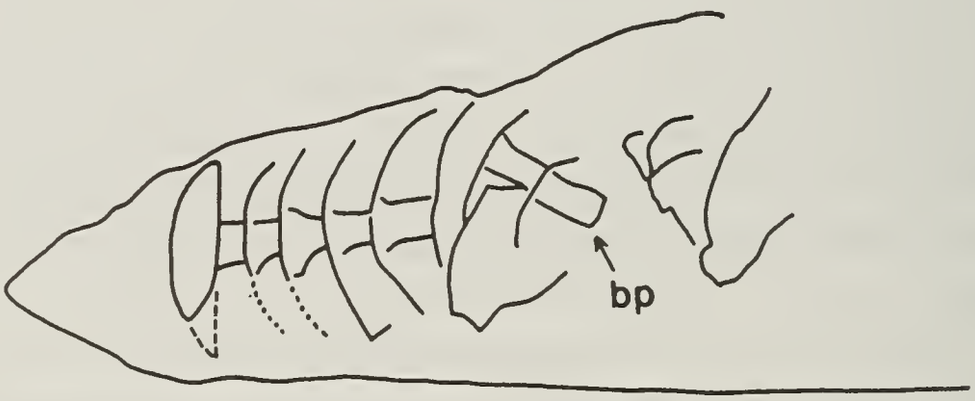
The earliest ontogenetic stages of the phragmacone show adapically tapering connecting rings that originate in a circle on the adoral surface of the preceeding septum surrounding the smaller diameter ventral perforation for the passage of the siphonal tube. The taper reduces their diameter so that they are slightly larger than the ventral perforation in the adapical surface of the succeeding septum into which they locate, seemingly forming a butt-joint (Figs. 1b & 1c). The rings are colourless and translucent; they have well-marked longitudinal striations along their length.

The presence of connecting rings rather than macrochoanitic septal necks is inferred from the fact that the phragmacone breaks into sections where a rings locates into the adapical surface of a septum - a point where a macrochoanitic septal neck would be strongest (see Fig. 1b).

Fig. 1.

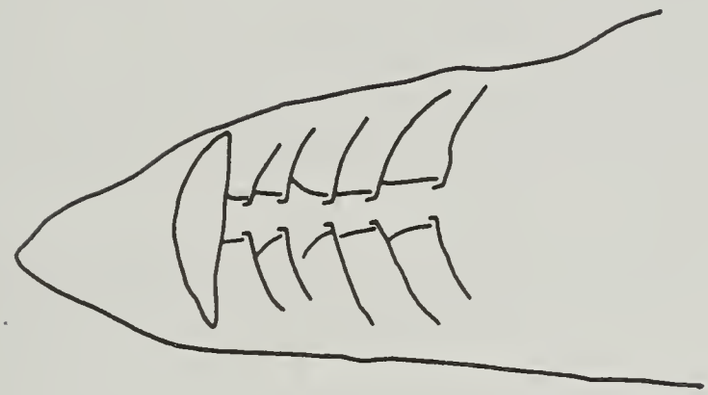


1a. Diagrammatic cross section in the ventral-dorsal plane through a pair of connecting rings on specimen MFD(S1)21/1. The aperture is towards the right. The nature of the junction of the septum with the ventral side of the connecting rings in conjectural; that with the dorsal margin was clearly seen. Note the way that the adoral end of the connecting rings flare out and back-up the adapical surface of each septum. The dashed lines represent traces of septa. Legend: cr_n, connecting ring n; s_n septum n.

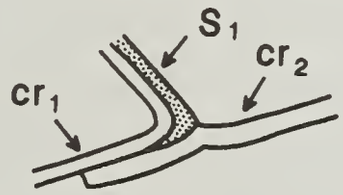


1b. Tracing from a photograph of the alveolar cavity showing the protoconch, terminal membrane, pro-septum and initial septa in dorsal view. Specimen MFD(S1)21/1. A pile of collapsed and broken septa is shown at the adoral end of the illustration. Note the way septa have broken away from their preceeding adapical connecting ring immediately at their junction with the septal surface. Legend: *bp* breakage-point.

Fig. 1.



1c. Diagramatic cross section through partially restored structure shown in Fig. 1b. In early chambers, septa curved adorally (at least along the ventral surface of the alveolus) until they met and fused with the suceeding septum, (not shown here because the precise nature of the junction could not be seen clearly).



1d. Detail of Fig. 1a, showing junction of adoral end of a connecting ring, ventral portion of septum, and adapical end of the succeeding connecting ring. Note the short, orthochoanitic septal neck, and the adoral ridge (labelled *ar*) on the connecting ring at the base of the septum. The constant thickness of the connecting rings, especially beneath the adoral ridge, is inferred on grounds of parsimony. Legend as for figure 1a.

12 - 15mm from the protoconch.

At this stage, the connecting rings are 0.9mm long (inferred to correspond to septum ?30) and between 0.01 and 0.013mm thick. Successive (adoral) sections of the connecting rings originate in a band 0.19 mm wide within the most adoral end of the preceeding ring (Fig. 1a) and are closely adnate against the ventral surface of the phragmacone for most of their length. The connecting rings are now tubular rather than conical, with an adapical dorsal flexure making them gently "S" shaped in lateral profile (Fig. 1a).

The rings are translucent and colourless, with well-marked longitudinal striations (0.014mm wide) along the full length of the surface of the connecting ring; conspicuous trains of dark red granules are concentrated in the grooves of the striations on the adapical half of the ring. There are 70 - 80 closely-spaced, transverse wrinkles (growth-lines?) per mm around their circumference, together with many very minute, evenly spaced perforations (Plate. 1).

Owing to both the available specimens missing the section of phragmacone between the 8th and ?30th septum there is no evidence how the transition from "butt-jointed", conical connecting rings to the overlapping tubular rings is made.

?25 - 43mm from the protoconch

By extrapolating the rate of increase in the length of the connecting rings measured on specimen MFD(S1)21/1, the sequence of seven connecting rings in specimen MFD(S1)21/2 can be inferred probably to represent the 43rd - 50th camerae, and to have been located originally some 25 - 43mm from the protoconch, beyond the anterior margin of the guard.

The rings are gently hourglass shaped, and can be resolved into five regions on the basis of their surface morphology and thickness (Fig. 2):

1. A rough, bi-laminate section marking the region where the ring originates within the preceeding ring.

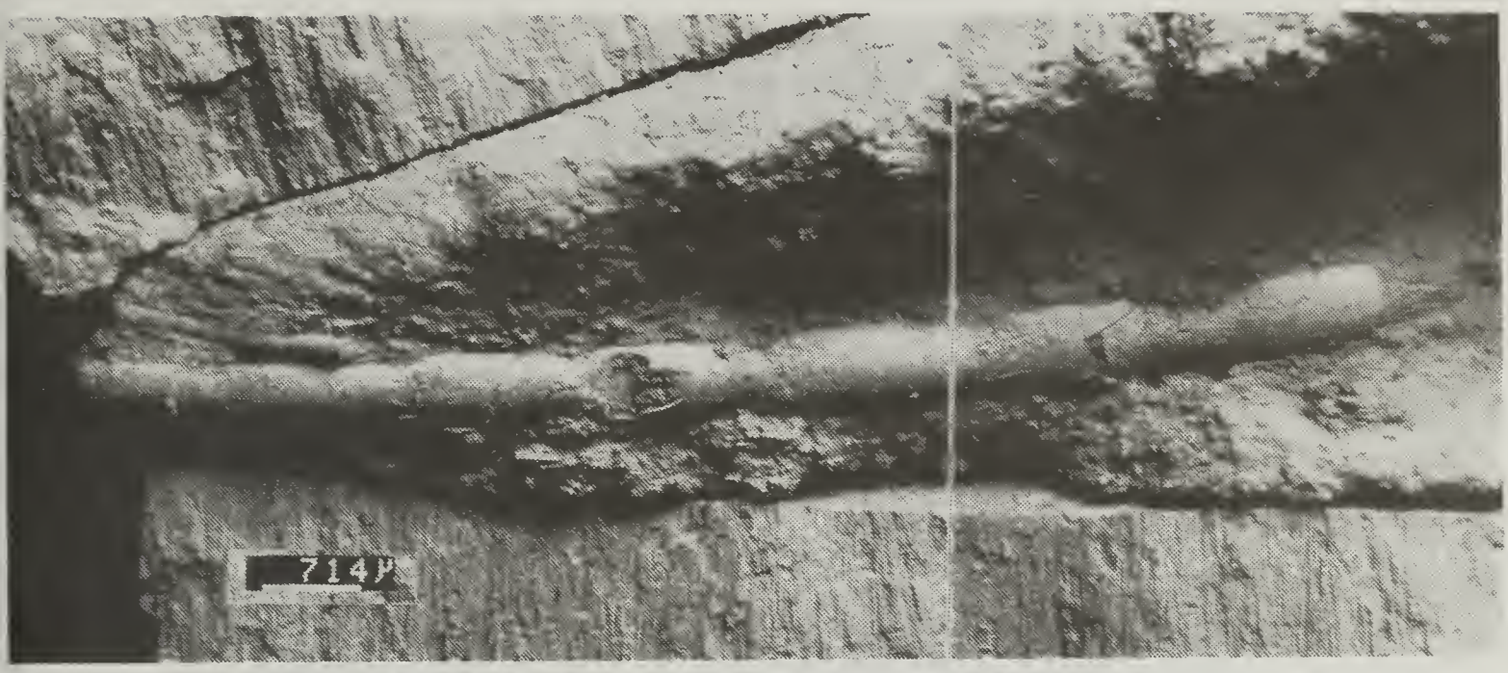


Plate 1. Guard split in ventral-dorsal plane to reveal embedded in fine-grained phosphatic chalk a sequence of seven connecting rings adjacent to the dorsal margin of the alveolus, (i.e. not in life position - see text for discussion). The small, spindle-shaped object at the base of the alveolus is a foraminiferan. BM(NH) specimen no. C59589.

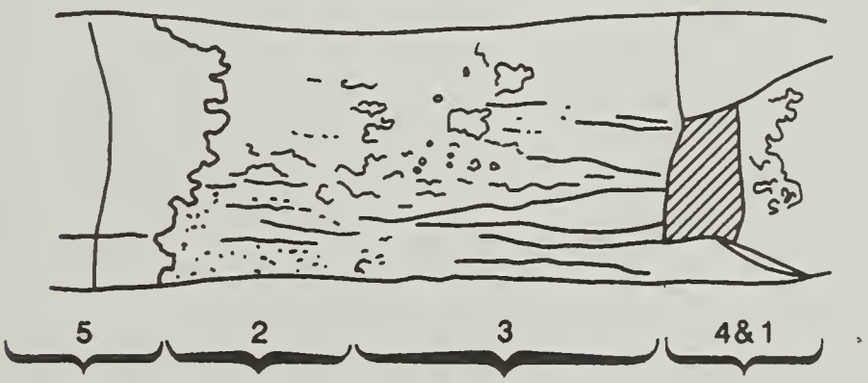


Fig. 2. Diagram of a connecting ring from the adoral end of BM(NH) specimen C59589 prepared using the photograph produced as Plate 2. The units labelled 1-5 are those used in discussing septal necks in the text.

2. A bi-laminate section from the adoral end of section (1) to the median constriction. At optical wavelengths the surface appears notably duller and less lustrous than the succeeding section. SEM photography shows this to be due to numerous closely spaced longitudinal wrinkles. This section also has the greatest concentration of perforations which traverse both layers. These perforations are often paired.

3. A smooth section from the median waist to the point where it overlaps the region where the next ring originates. The surface is very lustrous at optical wavelengths. SEM photography shows it to be smooth, with no or very few wrinkles and lacking perforations. It seems also to be uni-laminate.

4. A smooth section overlapping the point where the next ring originates. It is seemingly much thickened (Plate 2) and homogeneous.

5. A short section where the ring becomes bi-laminate and perforate again.

The rings are opaque, creamy-white, and apparently more extensively calcified than those of younger ontogenetic stages. The sections have a pale brown colour band in the region of overlap giving the siphuncle a striped appearance (Plate 3).

SEPTA

Mural parts of septa

Proseptum and terminal membrane.

The proseptum cannot be clearly distinguished from the terminal membrane on the only specimen available, though the circular scar left by the foot of the siphuncle can be seen clearly. It occupies 38% of the diameter of the proseptum/terminal membrane, which is 0.49mm in diameter.

Septa of later ontogenetic stages.

0 - 4mm from the protoconch.

The septa are gently convex adorally over 90% of their diameter but curve sharply adorally at their junction with the alveolus where they continue along its

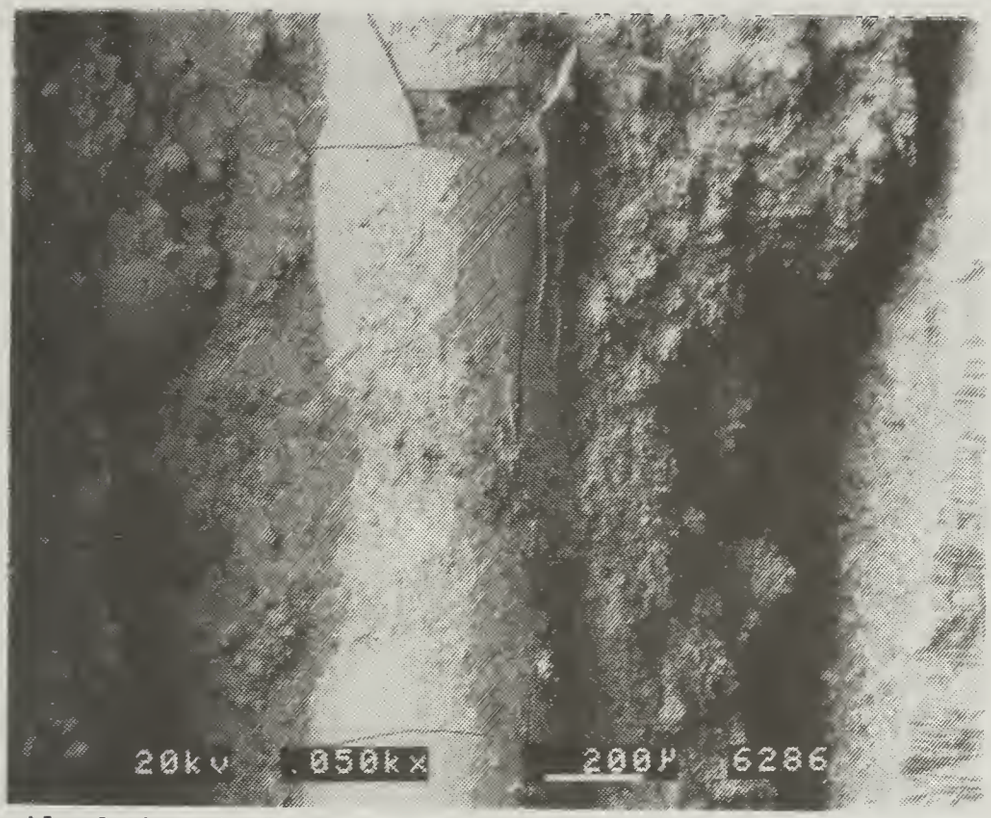


Plate 2. Detail of the sixth connecting ring showing the surface morphology, and a fracture revealing a marked local thickening of the ring wall at the point of overlap. This fracture enables the true length of the succeeding connecting ring to be determined.

Plate 3. Detail of plate 2 showing longitudinal wrinkles in the laminated ring wall and the perforations through its surface. Note the tendency for the pores to be paired.

surface until they meet the adapical surface of the succeeding septum (Fig. 2). The edges of the septa thus constitute the exterior wall of the phragmacone (adapically and ventrally, at least). In this region, the septa intersect the connecting rings at an angle of approximately 80.

12 -15mm from the protoconch

The septa are bi-laminar, as can be seen where the layers have exfoliated. The adoral layer is twice as thick as the adapical and consists of the flared adoral end of the preceeding connecting ring. It is not possible to determine from the available material how extensively the connecting ring covered the adapical surface of the septum (Fig. 1a). In this region, the septa intersect the connecting rings at an angle of 45.

4.4 - 14.4mm from the protoconch

Traces of at least thirteen septa can be seen preserved as rings firmly fused to the side of the nacreous, irridescent "white layer" lining the alveolus in a 10mm region starting 4.4mm from the protoconch. The interval between these increases adorally from 0.9 to 1.9mm (Table 1). This type of septal trace has been noted by several previous workers, who illustrated examples (Birkelund, 1957, Christensen, 1975).

Septal necks

Neither of the available specimens preserve evidence of the contact between septa and connecting rings through all ontogenetic stages; the material shows that septal necks were orthochoanitic for the first two - seven camerae, and that septal necks were still orthochoanitic 12 - 15mm from the protoconch (camera 30, approximately).

DISCUSSION

During ontogeny the connecting rings change from being conical and arranged in a rectilinear line, to tubular and flexuous (ventro-dorsally), before finally becoming slightly hourglass-shaped in gently bowed series. Over the same stages the individual rings become more complex, their surface differentiating into as

TABLE 1. Measurements in mm of septal spacings and connecting ring lengths

Specimen:	1		2		3
N	D	S	D	S	D
1	0.21	0.21	4.40	-	-
2	0.29	0.08	4.85	0.45	-
3	0.39	0.10	5.35	0.50	1.30
4	0.49	0.10	5.85	0.5	01.30+
5	0.65	0.16	6.55	0.70	1.43
6			7.40	0.85	1.49
7			8.05	0.65	1.82
8			9.00	0.95	
9			9.90	0.90	
10			10.90	1.00	
11			12.00	1.10	
12			13.00	1.00	
13			14.00	1.00	

"N" is the number of the septum/connecting ring counting from the adapical end of the protoconch (1 and 2), and from the adapical end of the connecting ring sequence (3). "D" is the distance in mm from the adapical end of the protoconch. "S" is the spacing of the septa. 1 - 3 refers to the specimens below.

1. First 5 septa of specimen MFD(S1)21/1.

2. Measurements of traces of 14 consecutive septa on the walls of the alveolus of specimen MFD(S1)21/1 between 4.40 and 14mm from the protoconch, believed to represent (approximately) the 21st - 34th camerae.

3. Length of some of the connecting rings on specimen C59589. The rings overlap one another by approximately 12% - the seventh ring is 2.02mm long.

many as five different regions by late ontogeny, where the adoral ends may be markedly thickened. Most interesting is the change in the position of the region where new rings originate. In earliest ontogeny rings originate in a circular region on the adoral surface of the preceeding septum; by no later than about camerae 30 the rings are originating on the interior surface of the preceeding ring - adapical to the preceeding septum. Frustratingly, the transitional region is not preserved in either of the specimens available.

Septal necks are apparently orthochoanitic throughout ontogeny. The mural parts of the septa are poorly preserved in the available material except where they join the connecting rings and the walls of the alveolus. Those septa that are preserved appear hyaline, and their adoral surface is often irridescent. In mid-ontogeny the adapical surface is backed-up by the flared adoral end of the preceeding connecting ring, though how extensively this covered it is indeterminate. Judging by the rate at which it thins dorsally, the collar could have covered as much as 50% of the surface. Septa appear to have been absent from the region beneath the proostracum; certainly the connecting rings lack the well-marked adoral ridge immediately in front of the septal neck (Figs. 1a & 1d).

Comparisons with other Mesozoic belemnites.

Data on the structure of the phragmacone of European Mesozoic belemnites is scarce, not least owing to the rarity of usable material. This account draws heavily on results reported by Jeletzky (1966) and Mutvei (1971).

1. Overlapping connecting rings.

The degree to which connecting rings overlap is greater than anything known to Jeletzky (1966), though he figured sections of *Belemnites (Belemnites) paxillosus* Lamarck 1801, var. 'C' of Schwegler (1962, pp. 138/9, fig. 19, 30) from the Upper Lias of Gundershofen, Germany, in which successive connecting rings originate only just inside the adoral end of the proceeding ring. The overlap is from 10 - 12% of the length of a ring in *B. cf. langei*, which is much greater.

2. Thickened connecting rings.

Dimitobelus lindsayi (Hector, 1878) from the Piripatuan (= Campanian) of South Island, New Zealand shows a slight thickening of the adapical end of adult connecting rings - in contrast to the adoral thickening in late ontogenetic stages noted here. No other belemnite is known to have locally thickened connecting rings.

3. Flared adoral ends of connecting rings.

No other belemnite is known to have extensive flaring of the adoral end of the connecting ring.

PRONENANCE AND TAPHONOMY

The two specimens described here probably come from the lower part of the pit at Caistor St. Edmund. This site is well known to local Cretaceous workers, and produces a rich fauna in what is often strongly phosphatised chalk. Experienced gained with examining the belemnite sample collected from Marlingford (100+ specimens) suggests that perhaps 2% of specimens should preserve at least some recognisable remains of the phragmacone if the alveolus is prepared sufficiently carefully. Research quality material, regretably, is much scarcer.

At the Caistor St. Edmund horizon the better material was distinguished by having fresh-looking belemnite guards (i.e. those lacking borings or encrustations), with obvious yellow powdery phosphatic chalk in the vicinity of the alveolus, and, when split in the ventral-dorsal plane, ring-like traces of the septa on the alveolus. The chalk plug infilling the alveolus, must be carefully prepared to reveal any traces of the siphuncle and septa. This is best done after the chalk plug has been softened by thoroughly soaking it in water; it may then be developed with a dissecting needle whilst being examined under a stereoscopic microscope at low magnification.

ACKNOWLEDGEMENTS

I would like to thank Dr Paul Taylor of the Brtish Museum (Natural History) for preparing the SEM photographs.

REFERENCES

BIRKELUND, T. 1957 Upper Cretaceous belemnites from Denmark. *Biologiske Skrifter udgivet af Det Kongelige Danske Videnskabernes Selskab* 9(1). 69pp. Copenhagen.

CHRISTENSEN, W. K. 1975. Upper Cretaceous belemnites from the Kristianstad area in Scania. *Fossils and Strata*, Number 7. Oslo.

JELETZKY, J.A. 1966 Comparative morphology, phylogeny, and classification of fossil Coleoidea. *Univiversity of Kansas Palaeontological Contributions, Mollusca, Article 7.* 162pp. Kansas.

MURRAY, J. W, (ed) 1985. Atlas of Invertebrate Macrofossils. Longman.

MUTVEI, H. 1971. The siphonal tube in Jurassic Belemnitida and Aulacocerida. *Bull. of the Geological Institutions of the Unversity of Uppsala* **3**, 27-36.

GLOSSARY

adapical = towards the apex of the guard

adnate = laying in contact with a surface

adoral = the opposite of adapical: towards the vicera/orifice

alveolus = The conical hole in the adoral end of a belemnite guard in which is located the phragmacone.

camera [=chamber] = Space bounded between two septa and the walls of the alveolus

coleoid [synonym: endocochlea] = Cephalopods with an internal phragmacone (q.v.).

macrochoanitic = A term used to describe adapically-directed septal necks (q.v.) which are so long that they extend the full length of a camera, and part-way into the septal neck of the preceeding septum.

orthochoanitic = A term to describe short, adapically-directed septal necks.

phragmacone = The chambered portion of a coleoid shell; it is exactly homologous to the ammonite or nautiloid shell

proostracum = Blade-like outgrowth of the dorsal side of the phragmacone.

protoconch = The first formed chamber (camera).

septal necks = A flared collar surrounding the hole in a septum through which the siphuncle passes.

For a well-illustrated, up-to-date, readable introduction to cephalopods and the terminology applied to them see House, in Murray (1985).

THE OCCURRENCE OF THE ACROTRETIDE BRACHIOPOD GENUS *?Discinisca* IN THE EAST NORFOLK CHALK.

Paul S. Whittlesea

8 Eaton Old Hall
Hurd Road
Norwich NR4 7BE

ABSTRACT

The inarticulate brachiopod *?Discinisca* Gray 1840, is recorded from the upper Upper Campanian and lower Lower Maastrichtian Sponge Beds of Norfolk, eastern England. This is the first record of the genus from the boreal Upper Cretaceous of Europe.

INTRODUCTION

Inarticulate brachiopods are common fossils throughout much of the Upper Chalk, though they are never diverse. Nearly all are members of the Craniacea and have calcareous valves, of which the ventral is usually cemented to a hard substrate, at least during juvenile growth stages. Specimens of species with chitinophosphatic valves, such as *Lingula*, are much rarer.

The Discinacea have a long geological history extending at least as far back as the Ordovician (Williams *et al*, 1965). The genus *Discinisca* survives today, and records of it are known from the Jurassic as bioimmurations on the attachment scars of oysters (P. D. Taylor, pers. comm., 1990). Surprisingly, the genus appears not to have been recorded previously from the Upper Cretaceous.

The discovery of a specimen of *Discinisca* during a field trip to Sidestrand (O.S. grid reference TG 255 404), organised by the Geological Society of Norfolk is thus an important record. Since the initial discovery, three further specimens have been collected extending the stratigraphical range down into the Upper Campanian, and three others have been recognised in material collected recently, but previously overlooked.

All the specimens come from the East Norfolk chalk which comprises the outcrop and subcrop of the zones of *Belemnitella mucronata*, *Belemnitella*

langei and *Belemnella lanceolata* in Eastern Norfolk, (See Wood, (1988), for a discussion of the history of the stratigraphy of the chalk of Eastern Norfolk). Most of the specimens have been donated to the British Museum (Natural History); where this is the case their accession numbers are given after those of the author.

MATERIAL

Specimen 1, author's catalogue number SS(SB)253/1, BM(NH) accession number BB86849.

A complete, undamaged, chitinous dorsal valve, 4mm in diameter. It is attached to the interior of a fractured echinoid test enclosed in chalk collected on Sidestrand beach. From its distinctive lithology it is concluded that it is derived from the Sponge Beds at Sidestrand on the North Norfolk coast. The Sponge Beds belong to the lower Lower Maastrichtian zone of *Belemnella lanceolata* (Peake & Hancock, 1961, Johansen & Surlyk, 1990).

Specimen 2, author's catalogue number: SGH(F8.7)126/1.

A specimen, 4mm in diameter. It is attached to the exterior of an echinoid test in association with other epifaunal elements. The dorsal valve is broken to expose a composite internal mould one third of which consists of a clear calcite crystal moulded to the shell with a smoothly curved junction with the remaining chalk infill. Only a rim of chitinous shell remains. From Sheringham foreshore; Campanian, zone of *Belemnitella langei*, Upper Beeston Chalk (Peake & Hancock 1961, Johansen & Surlyk, 1990).

Specimen 3, author's catalogue number SGH(F12.5)126/2. BM(NH) catalogue number BB86970.

A specimen, 2.5mm in diameter. It is a complete dorsal valve preserved by bioimmuration on the attachment scar of an oyster *Pycnodonte vesicularis* (Lamarck). It retains clear impressions of setae radiating outwards from the margin of the valve. From Sheringham foreshore; Campanian, zone of *Belemnitella langei*, Upper Beeston Chalk.

Specimen 4, author's catalogue number CM(?)2/1, BM(NH) catalogue number BB86971.

A tiny juvenile specimen, 2mm in diameter, preserved as a calcite internal mould. The apex of the dorsal valve has broken away thereby partially exposing to view the ventral valve. Fine striate growth lines are visible on the calcite of the mould. The specimen is attached to a guard of *Belemnitella langei*. The specimen was found in material dumped in Keswick chalk pit from the 1991 Castle Mall excavations in centre of the city of Norwich; it probably comes from a horizon low in the Beeston Chalk.

Specimen 5, author's catalogue number KW(?)138/1, BM(NH) catalogue number BB86973.

A large specimen, 6mm in diameter, preserved as a crushed shell plus calcite infill, attached to the guard of a belemnite, *Belemnitella mucronata*. Both valves are present; the ventral valve is visible by virtue of the dorsal valve being almost entirely broken away. From Keswick chalk pit, Keswick, near Norwich; upper Upper Campanian, zone of *Belemnitella mucronata*, low Weybourne Chalk.

Specimen 6, author's catalogue number KW(?)138/2.

A very poorly preserved specimen consisting of a crushed and fragmented dorsal valve attached to a belemnite guard. It is estimated to have been 5mm in diameter when complete. It shows traces of the ventral valve. Location and horizon as for specimen 5.

Specimen 7, author's catalogue number KW(?)138/3, BM(NH) catalogue number BB86971.

A small specimen, 2.5mm in diameter, attached to a belemnite guard together with a larger, broken individual overgrown by a serpulid, *Sclerostyla macropus* (Sowerby). Location and horizon as for specimen 5.

The pit at Keswick has recently been infilled by material excavated for the Castle Mall development project.

MORPHOLOGY AND PRESERVATION

The dorsal valve has a circular outline and the form of a simple right cone with an apical angle of about 55 degrees. In specimens greater than 2mm in diameter the posterior margin is noticeably straightened, as if truncated across a chord along an arc of 32 degrees, as measured on specimen number KW(T?)138/3.

The shell is very thin (0.03mm) and smooth, with a surface sculpture consisting of up to 130 very fine, closely-spaced growth lines per mm (Plates 1 & 2). These growth-lines may be broken into series of drapes, similar to the fila ornament noted by Williams & Holmer (1992) in some acrotretoid brachiopods. There are no other external morphological features of note.

The ventral valve has been found partially obscured by crystalline calcite inside the dorsal valve of most of the specimens. In the smaller specimens it is approximately one third the thickness of the dorsal valve and is moderately convex across the central two-thirds of its width. The thickness of the ventral valve is not observable in any of the larger specimens.

Impressions of some muscle attachment scars were found anterior to the foramen in one specimen (BB86973), which may be anterior adductors, though the specimen is too incomplete for this to be certain (Plates 3 & 4). Where the ventral valve is broken on this specimen it can be seen that there is a fibrous layer underneath the area covered by these (Plates 4 & 5) which is absent elsewhere.

In one of the large shells the foramen and surrounding collar is 1.25mm long and 0.37mm wide. In the same specimen, the foramen itself appears to be 0.62mm long and no more than 0.25mm wide. The opening is infilled with microcrystalline calcite so it is not possible to make more precise measurements (Plate 3). It is centrally located on the summit of the convex valve in the smaller specimens, and slightly more posteriorly located in the large specimen where it is surrounded by at least three major concentric ridge-shaped growth lines and many very much finer ones. No septum is visible.

Some eight to ten narrow, (0.025mm wide), clearly incised, straight grooves radiate posteriorly and laterally from the central end and sides of the foramen reaching to the edge of the valve. They probably represent traces of setae which are present in modern species of *Discinisca*. Slit-like

Acrotretide Brachiopod

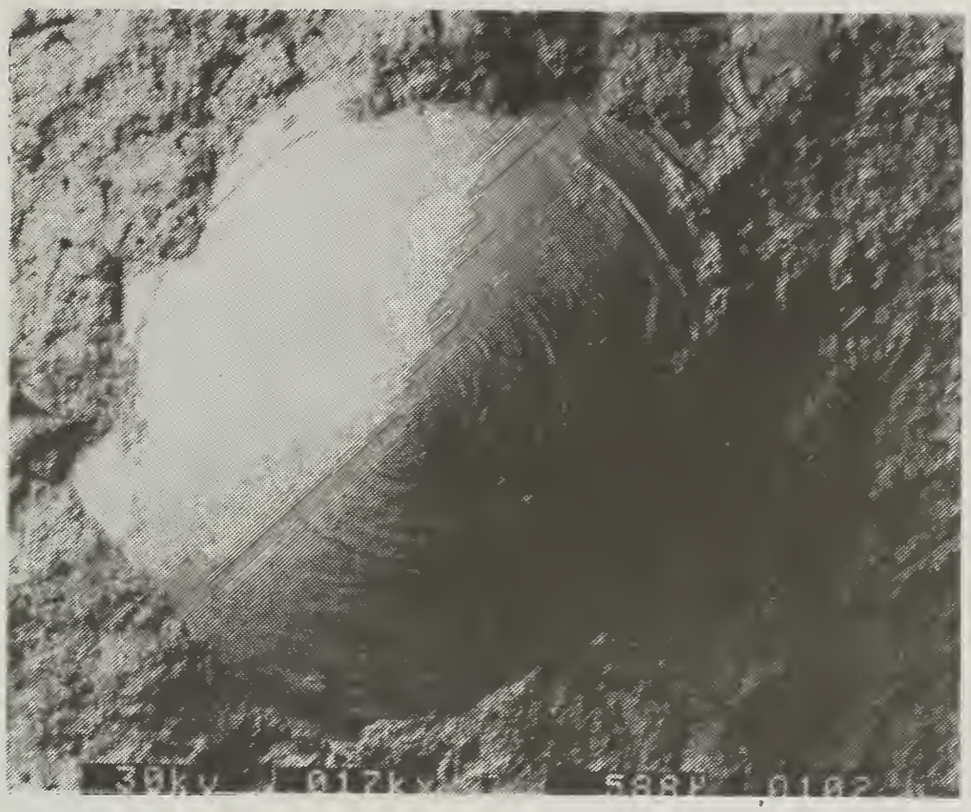


Plate 1. View of complete dorsal valve. Maastrichtian, zone of *Belemnella lanceolata*, Sponge Beds; Sidestrand beach, north Norfolk. Specimen no. BB86849.

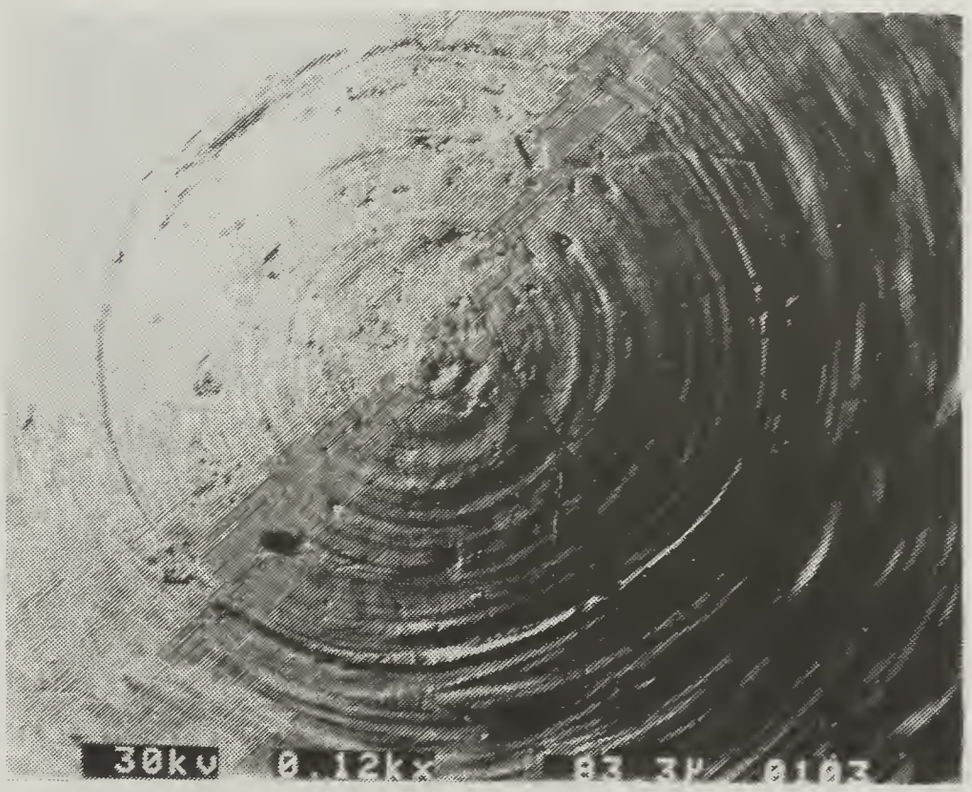


Plate 2. Detail of the apex of the specimen in Plate 1, showing closely-spaced growth lines.

Plate 3. View of broken ventral valve seen through the broken top of the dorsal valve. Impressions of at least six setae can be seen radiating from the margin of the ventral foramen, which is infilled by microcrystalline calcite. The imbricate structures exposed along the right-hand margin are neomorphic calcite crystals. Specimen no. BB86973.

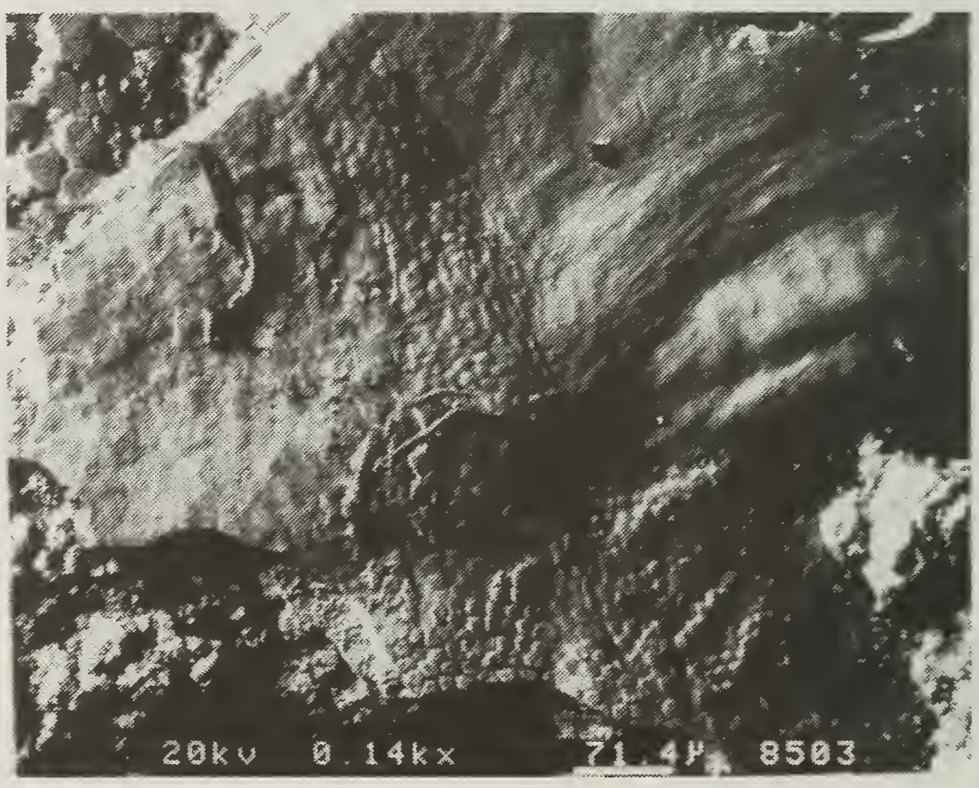


Plate 4. Detail of Plate 3 showing muscle attachment scars present just anterior of the foramen.

Acrotretide Brachiopod

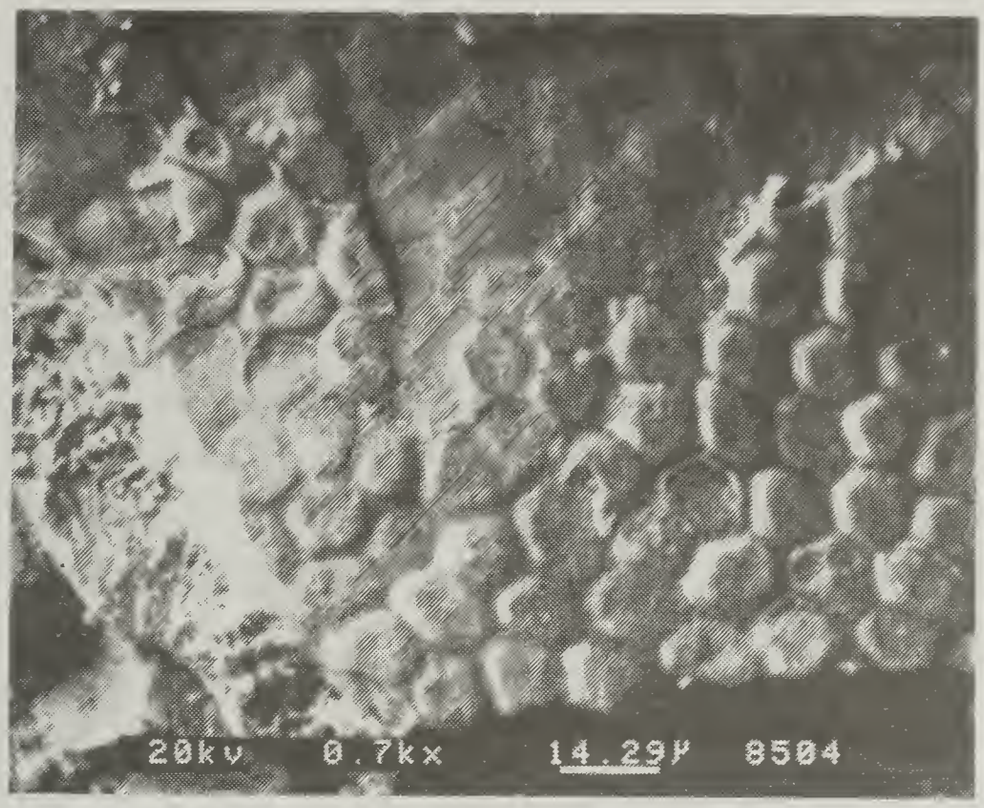


Plate 5. Detail of Plate 4, showing polygonal mosaic of blister-like shell ornament delimiting the muscle-scars. Note fibrous layer exposed beneath the muscle scars at the broken valve margin, which is apparently absent in areas not underlying these.

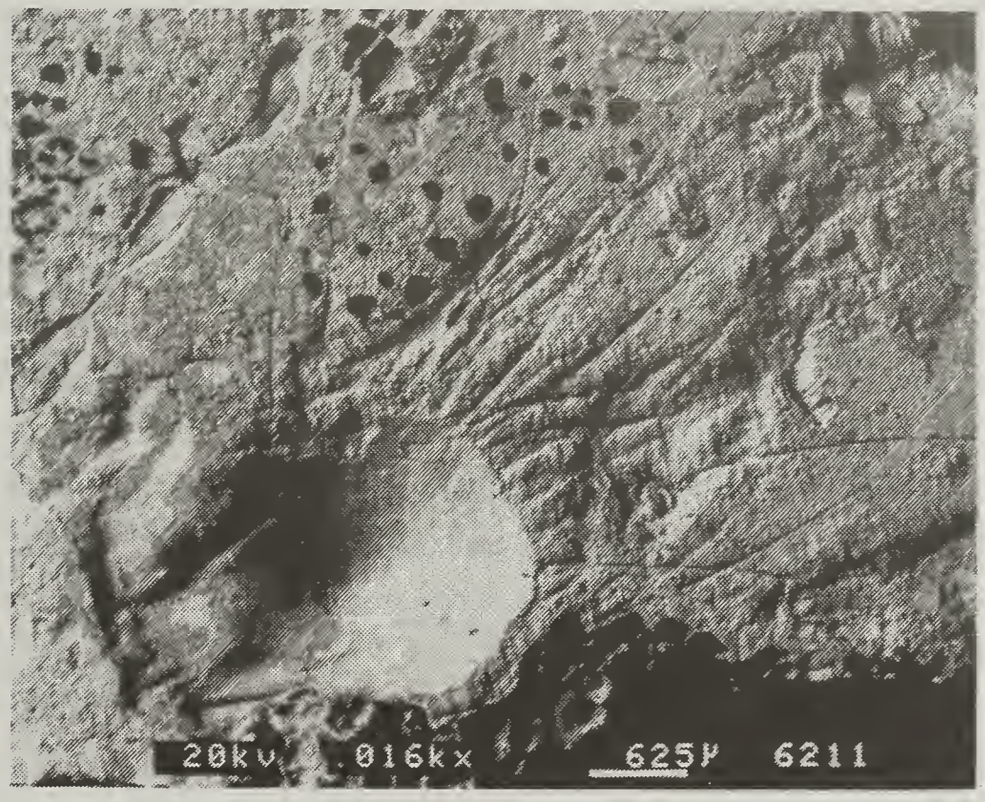


Plate 6. View of dorsal valve with sensory setae emerging from its periphery, preserved as a bioimmuration by the oyster *Pycnodonte vesicularis* (Lamarck). The uniserial organism at the lower right is an undescribed genus of ctenostome bryozoan. Specimen no. BB86970.

indentations, 0.025mm in width, spaced 0.5mm apart (where visible) in crystalline calcite along part of the periphery between the valves of one specimen, are also inferred to represent the former position of sensory setae. The number of setae is estimated to be a minimum of 12-20; specimen 3 shows clear impressions of at least 16 setae around one-third of the valve periphery; these extend up to 8mm from the margin (Plate 6).

The muscle scars on the interior of the dorsal valves were not examined owing to the risk of damaging the only complete specimen currently available. This is partially embedded in the extremely hard limestone that characterises the Sponge Beds. Moreover, on most of the broken specimens it could be seen that the valve was lined with euhedral calcite crystals which would frustrate any attempt to examine them.

All the specimens (except specimen 3, which is preserved as a bioimmuration) are found attached in presumed life position with the margin of the dorsal valve firmly pressed against the substrate. Very thin fragments of the shell are left adhering to the calcite internal mould, which is crystalline in places. Specimens 1 and 2 preserved the conical shape in the first instance because it was living inside a vacant echinoid test and in the second because it was protected by the overarching growth of an oyster, *Pycnodonte*.

DISCUSSION

Discinisca is one of the most intensively researched extant inarticulate brachiopods and a substantial literature exists. The modern species tolerate a wide range of depths and include some that are amongst the very few that can live just above the low tide mark, (Rudwick, 1962). All the specimens found come from horizons above major erosion surfaces produced during regressive phases of the boreal Late Cretaceous.

The diagnostic features that distinguish *Discinisca* from morphologically similar inarticulate brachiopods (such as *Discina* and *Pelagodiscus*) are the presence of a listrium, a foramen situated in a depression in the ventral valve, and a schizolophous lophophore.

It has not been possible to demonstrate the presence of a listrium in the ventral valve, because in all cases the ventral foramen is infilled with microcrystalline calcite. However, the foramen appears to be located in a shallow depression, which is not the case in species of *Discina*. The almost

perfectly circular dorsal valve with its centrally placed apex, thin chitinous shell, and small size suggests affinities with *Pelagodiscus* as well as with *Discinisca*, but modern species of that genus are typically abyssal and have a spirolophous lophophore (not determinable in fossil material). All other features are in agreement with those recorded for species of *Discinisca*. When suitable material becomes available it will be important to examine the muscle attachment scars on the valves to verify the generic determination.

SUMMARY

Discinisca may be of more widespread occurrence than the few specimens suggest, having simply been overlooked previously. Its lustrous orange-brown chitinous shell looks very similar in colour and lustre to that of a fish scale and could readily be mistaken for a fractured half vertebra. The conical calcite internal moulds resemble those of juvenile solitary scleractinian corals such as *Parasmilia* and *Coelosmilia*, however, their domed, hexalobate outline makes them easy to distinguish. Juveniles of these corals are common fossils on a variety of substrates throughout the Weybourne and Beeston Chalks. However, all specimens of *?Discinisca* found thus far show the fine growth striae clearly (Plates 1 and 2).

ACKNOWLEDGEMENTS

I would like to thank Dr. Paul Taylor, (British Museum (Natural History)) for drawing my attention to the Jurassic specimens of *Discinisca* in the museum's collections and for preparing, together with Tiffany Foster, the SEM photographs, and Finn Surlyk for comment and criticism on a draft version of this paper.

REFERENCES

JOHANSEN, M.B. and SURLYK, F. 1990. Brachiopods and the stratigraphy of the Upper Campanian and Lower Maastrichtian Chalk of Norfolk, England. *Palaeontology*, **23**, 823-872.

PEAKE N. B. & HANCOCK J. M. 1961 The Upper Cretaceous of Norfolk. In Larwood, G.P. and Funnell, B.M., (eds). *The Geology of Norfolk*. Transactions of the Norfolk and Norwich Naturalists Society, reprinted 1972 by the Geology Society of Norfolk with addenda and corrigenda.

RUDWICK, M. J. S. 1962 Notes on the ecology of Brachiopods in New Zealand. *Transactions of the Royal Society of New Zealand, Zoology*, **1**, 327-335.

WILLIAMS, A. et. al. 1965 Treatise on Invertebrate Palaeontology. Part H: Brachiopoda. University of Kansas Press and *Geological Society of America*, pp. 282-286.

WILLIAMS, A., & HOLMER, L. E. 1992 Ornamentation and shell structure of acrotretoid brachiopods. *Palaeontology*, **35**, 657-692, 7 pls.

WOOD, C. J. 1988 The stratigraphy of the Chalk of Norwich. *Bulletin of the Geological Society of Norfolk*, 38, 3-120.

GLOSSARY

Bioimmuration is a mode of preservation whereby the object of interest is preserved by being overgrown by another organism. The fossil is then represented as a mould in, or on the shell tissue of the overgrowing animal, typically an oyster. Where overgrowth happens very rapidly (it often does), soft tissues such as brachiopod setae (q.v.) and soft-bodied organisms (e.g. hydroids) may be preserved in exquisite detail, especially if overgrowth is accompanied by permineralisation.

Setae are chitinous bristles found around the valve margins of many live brachiopods. They arise from an invagination of the mantle groove at the valve margins.

AN ELEPHANT SKELETON FROM THE WEST RUNTON FRESHWATER BED (EARLY MIDDLE PLEISTOCENE; CROMERIAN TEMPERATE STAGE)

Anthony J Stuart

Castle Museum
Norwich NR1 3JU

ABSTRACT

West Runton is the most important fossil vertebrate locality of the Cromer Forest Bed Formation. The West Runton Freshwater Bed, the stratotype for the Cromerian temperate stage (early Middle Pleistocene), has yielded a rich vertebrate fauna, including: 8 fish taxa; 5 amphibians; 3 reptiles; 17 birds; and 43 mammals.

The discovery of a very large elephant pelvis in the West Runton Freshwater Bed was followed by an excavation which recovered about 25% of the skeleton of the same individual. The techniques used in excavating the bones and in their subsequent conservation are briefly described.

Work so far indicates a male *Mammuthus trogontherii* (an ancestor of the Upper Pleistocene woolly mammoth) with a shoulder height of up to 4 metres. Environmental evidence from fossil plants, molluscs and vertebrates indicates temperate mixed oak forest, some areas of grasses and herbs, and aquatic and waterside vegetation.

The distribution of the remains suggests that the carcass collapsed, and largely broke up before burial. The presence of hyaena coprolites, plus characteristic tooth marks on several bones, show that as it lay in the river the dead elephant was scavenged by spotted hyaenas *Crocuta crocuta*.

INTRODUCTION

The complex succession of marine and freshwater deposits known as the Cromer Forest Bed Formation (C.F.B.F.), occurs beneath the till along the coast of northeast Norfolk, extending into Suffolk. The 'Forest Bed' (the name comes from occasional finds of fossil tree stumps - Reid, 1882; 1890) has been famous for its fossil mammal remains since early in the last century (Owen, 1846; McWilliams, 1967; Stuart, 1982; in press; Lister, in press a; in press

b). Although at present many of the classic localities are obscured by sea defences, important finds are still made at West Runton and elsewhere.

West's (1980) impressive reinterpretation of the stratigraphy and palaeobotany of the C.F.B.F., utilizing palynology, has provided an invaluable framework for sorting out the sequence of vertebrate faunas. According to West the C.F.B.F. covers several climate-based stages, from the oldest to the youngest: Pre-Pastonian (cold); Pastonian (temperate); Beestonian (cold); and Cromerian (temperate), the deposits of which are succeeded by tills and outwash of the Anglian Glaciation. The Pre-Pastonian (the oldest) and Pastonian are of Lower Pleistocene age, whereas the Beestonian and Cromerian belong to the early Middle Pleistocene. West recognized a major stratigraphic hiatus within the sequence, between the Pastonian and Beestonian. This hiatus is also evident from the way that C.F.B.F. mammalian faunas fall into two very distinct stratigraphic groups (Stuart, 1982), lacking intermediate faunas which are known from Continental Europe.

Recent work suggests that the C.F.B.F. is even more complicated, including one or more early Middle Pleistocene temperate stages which are post- Cromerian, but still pre-Anglian (Meijer & Preece, in press; Stuart, in press).

THE WEST RUNTON FRESHWATER BED

Stratigraphy

This famous deposit, known since the early nineteenth century, has produced one of the richest Quaternary vertebrate faunas in Europe. So far it has escaped being obscured by coastal sea defences and continues to erode more or less naturally.

The West Runton Freshwater Bed occupies a broad channel about 200m across in section and up to about 2m thick, cut into sands and gravels attributed to the Beestonian Cold Stage. It is exposed at the base of the cliff (NGR. TG 187431) east of West Runton Gap (Woman Hythe). Details of the stratigraphy, pollen and plant macrofossil assemblages are given by West (1980). The channel filling is designated the stratotype for the Cromerian Stage.

The lithostratigraphy and biostratigraphy (pollen) of the West Runton Freshwater Bed is summarized in Table 1; and the pollen assemblages and vegetational history shown in Table 2. The basal bed of the channel filling,

Bed	Maximum thickness (metres)	Substage	Lithology	Environment
g	0.3[1]		shelly silt	fluvial
f	1.32	Cr IIa, Cr IIb	sandy detritus mud	freshwater (low energy)
e	0.7[2]		shelly sand	fluvial
d	0.85	Cr Ib - Cr IIb	sandy detritus mud with reworked silt clasts	fluvial
c	0.75		shelly sand	fluvial
b	0.07[3]	Cr Ia - Cr Ib	stony detritus mud	freshwater (low energy)
a	0.9	l Be a - Cr Ib	calcareous silt	lacustrine

[1]Occurs only at eastern end of section

[2]Occurs only very locally at western end of section

[3]Occurs only locally at eastern end of section.

Table 1. Stratigraphy of the West Runton Freshwater Bed (slightly modified from West, 1980).

Substage	Characteristic pollen taxa	General characteristics of vegetation
Cromerian, Cr IIb	oak-elm-lime	mixed oak forest with some herbaceous vegetation
Cromerian, Cr IIa	pine-oak-elm	conifer-deciduous forest with some herbaceous vegetation
Cromerian, Cr Ib	pine-elm	pine-birch-elm woodland
Cromerian, Cr Ia	birch-pine	birch-pine woodland
Late Beestonian, l Be b	grass-sedge-birch	grassland with birch
Late Beestonian, l Be a	grass-sedge *-Artemisia*	herb-rich grassland,

Table 2. West Runton Freshwater Bed; pollen-based Substages and vegetational succession (data from West, 1980). NB aquatic, reedswamp and fen vegetation is represented throughout the sequence.

bed a (of West, 1980), occurs only in a limited area near Goss' Gap near the eastern end of the exposure. It comprises freshwater marls with pollen assemblages assigned to the late Beestonian Cold Stage. On its eroded surface rest West's beds b to e, fluvial shelly organic muds and sands with numerous reworked silt clasts and small pebbles (mainly flint), with pollen spectra essentially of substages Cr Ib - Cr IIa. The clast size decreases upwards and the upper part of the deposit, bed f, comprises detritus muds (shelly in part), mainly of substage Cr IIb age. The altered top of the bed, possibly a palaeosol, indicates a substantial period of subaerial exposure prior to marine deposition of the overlying basal gravel ('Monkey Gravel') and thin bedded silts and sands. The top of the Freshwater Bed is extensively bored by the marine mollusc *Mya truncata* L. Occasional shells can be seen in life position.

Vegetational History

The Freshwater Bed pollen (Table 2) and plant macrofossil assemblages (West, 1980) are from the first half of a temperate interglacial stage. Pollen assemblages from substage Cr Ib indicate woodland with pine, elm, birch, extensive herbaceous vegetation and restricted fen and reedswamp. In substages Cr IIa and Cr IIb this vegetation was succeeded by a more diverse woodland, with oak and other thermophilous trees more widespread, persistent local open habitats, and fen and reedswamp adjacent to the river.

Vertebrate Fauna

Small-vertebrate remains are fairly common, and the majority have been found by wet-sieving the sediments. Large-mammal remains are much rarer, but over the years numerous bones and teeth have been collected, especially when the fossils have been exposed after a combination of gales and high tides has eroded the cliffs.

The list of vertebrates from The Freshwater Bed has been significantly extended in the last few years (Table 3) (Stuart, 1992a; in press). J.A. Holman has worked on the reptile and amphibian material and added *Rana arvalis* moor frog, and *Rana ridibunda* or *R. 'esculenta'* marsh or edible frog to the list (Holman, Clayden & Stuart, 1988).

Recent additions to the mammal list include: *Nyctalus noctula*, noctule bat; *Pliomys episcopalis*, extinct vole; a small hamster, species not yet

determined; *Macaca sylvana*, macaque monkey; and *Megaloceros savini*, giant deer (Stuart, 1992a). In a major review of European Quaternary otters, Willemsen (1990) has referred the West Runton material to the extinct species *Lutra simplicidens*. Carnivores are clearly underrepresented taxonomically in the collections considering the wide variety of available prey.

Sparse small-vertebrate remains have also been found in the marine 'Monkey Gravel' which rests directly on the Freshwater Bed. This material has probably been reworked from the West Runton Freshwater Bed.

To date 43 mammalian taxa, 17 birds, 5 amphibians, 3 reptiles and at least 7 fishes are recorded from the West Runton Cromerian. Some of the bird identifications (C.J.O. Harrison, 1979) may be questioned on the grounds of insufficient material. The fish identifications listed here should be regarded as provisional; the material is at present under study by B. Irving.

DISCOVERY AND EXCAVATION OF THE ELEPHANT

Although thousands of vertebrate remains have been recovered from the West Runton Freshwater Bed, until recently only very sparse elephant material had been found. Other C.F.B.F. localities have yielded elephant remains in abundance, but all have been isolated finds, never several bones recognized as belonging to the same individual.

This situation changed dramatically in 1990, with the discovery of the most spectacular find ever from the C.F.B.F. (Stuart, 1992b; Driscoll & Stuart, 1993).

On 13th December 1990, after a combination of gales and high tides had eroded the cliffs, Mr and Mrs H. Hems found an exceptionally large bone partially exposed in the West Runton Freshwater Bed. When excavated, the bone proved to be the pelvis of a very large elephant. Further excavation revealed one other bone, a beautifully-preserved left astragalus. On the likely assumption that these bones were part of the same skeleton, it was anticipated that more bones might be exposed in the future, so the find spot was kept under observation.

On Boxing Day 1991, just over a year after the discovery of the pelvis, further cliff erosion exposed more bones which were found by another amateur geologist, R. Sinclair. With the help of other collectors, he managed to recover a right scapula, right fibula, three vertebrae and several ribs. Realizing that many more bones probably lay in the cliff, and that a proper

excavation should be carried out, they ceased digging and backfilled their excavation. Having been contacted on New Year's Day 1992, the author hurriedly organized a rescue excavation as any bones that remained were at risk from the next spring tide.

Having obtained the necessary permissions from the landowner Mr D.T. Abbs, North Norfolk District Council and English Nature (the site is a geological SSSI.), in January 1992 a controlled excavation was carried out by staff from Norwich Castle Museum and Cromer Museum in collaboration with several volunteers. Loose material which had fallen from the cliff was first removed using an hydraulic digger. The excavation, which continued for more than two and a half weeks, recovered many more bones *in situ*, including the mandible, much of the vertebral column, several ribs, the right ulna, and part of the right humerus. About a quarter of the skeleton has been recovered so far (Fig. 1).

As the bones were exposed, each was photographed *in situ*, recorded on a plan of the site, encased in a jacket of plaster and scrim for support, and numbered prior to lifting. Wooden splints were used to give additional support to the larger bones. The direction of magnetic north was also marked on the plaster jackets as an additional check on the orientation of the finds. Bones were removed from the beach in J.D. Clayden's pickup, and stored in his garage at West Runton until they could be transported to the Castle Museum.

At the end of each day all exposed bones were carefully covered with polythene sheets and sandbags to protect them from the elements and to provide some measure of security. Although there were several hundred visitors during the course of the excavation, there was no serious interference with the site. After only two days of excavation heavy rain and high winds caused a cliff fall which buried the site, but fortunately the precautions taken to protect the exposed fossils proved successful and the fall caused no significant damage. Three days later, after loose material had again been cleared from the site by hydraulic digger, the excavation was resumed.

In nearly all cases bones were seen to rest on the surface of the sandy detritus muds with reworked marl clasts ('bed e'), although because of their large size many bones projected some distance into the overlying detritus muds ('bed f'). None was found at a lower horizon within the Freshwater Bed.

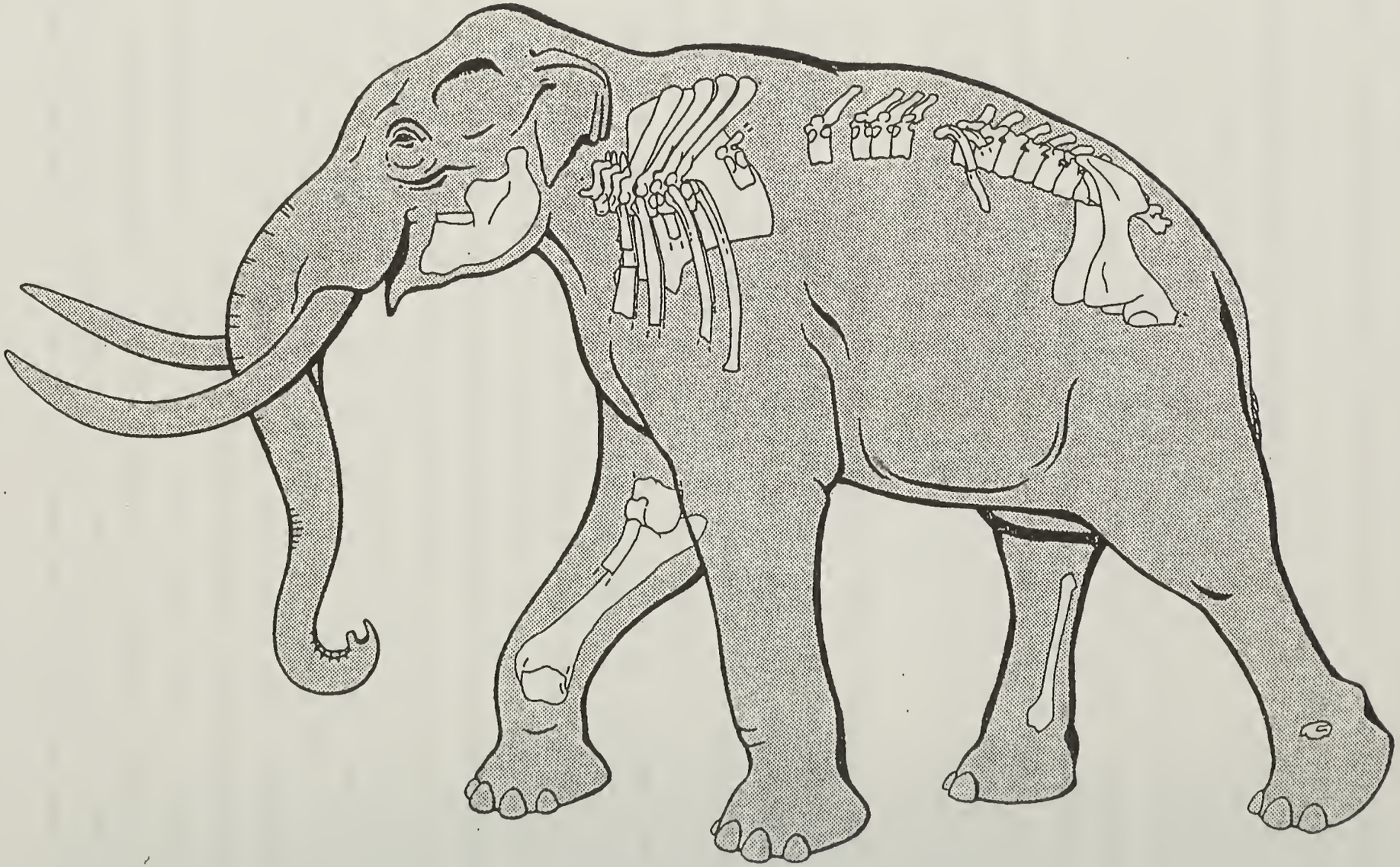


Fig. 1. Outline restoration of West Runton elephant *Mammuthus trogontherii*, showing positions of bones recovered 1990-1992. Illustration by Samuel Brown.

Sparse material of other species - bovid, cervid and rhinoceros *Dicerorhinus etruscus* (a cheek tooth fragment) - was also recovered from the excavation. Such material is common throughout the Freshwater Bed.

CONSERVATION

The conservation of the 1990-1992 finds is still in progress at the Castle Museum.

Although the surface preservation on most bones is excellent the majority were cracked or broken in situ, due to post-depositional compaction, which necessitates very careful treatment. After extraction from its plaster jacket each bone has been cleaned of sediment, and most have been impregnated with 'Paraloid' B72 solution in acetone (10% vol./vol.). Some of the first bones to be found were treated with an aqueous solution of PVA, but this method (good for consolidating wet bones) was less satisfactory than using 'Paraloid'. Fragmented bones, in many cases held in position by the plaster jacket, have been reassembled using 'Paraloid' glue. A resin and glass fibre 'cradle' was made to support the lower jaw. Similar supports are planned for other large bones.

THE ELEPHANT AND ITS ENVIRONMENT

Research on the find is in its early stages. Nevertheless, some preliminary observations can be made here, bearing in mind that views may change as new data accumulate.

The pattern of the molars, vertebral column and other characters demonstrate that the West Runton specimen is species of mammoth *Mammuthus* rather than straight-tusked elephant *Palaeoloxodon antiquus* Falconer & Cautley. The mammoth lineage is from the (mainly Lower Pleistocene) 'southern elephant' *Mammuthus meridionalis* Nesti to the so-called 'steppe mammoth' *M. trogontherii* Pohlig (Middle Pleistocene) to the well-known woolly mammoth *M. primigenius* Blumenbach (Middle and Upper Pleistocene). Evolutionary trends include a progressive increase in the number of plates in the molars, accompanying reduction in enamel thickness, and progressive shortening of the mandible (Lister, in press c). The presence of at least 16 plates (those visible on the worn occlusal surface) in the molars of the West Runton specimen, the relatively high crown height and relatively short mandible all suggest the species *Mammuthus trogontherii* (A.M. Lister, pers. comm. 1993).

Table 3. Vertebrate Fauna of the West Runton Freshwater Bed

PISCES (provisional identifications) (Stuart, 1975; 1988; Stinton, 1985)

1. *Esox lucius* L., pike
2. *Gasterosteus aculeatus* L., three-spined stickleback
3. *Anguilla anguilla* (L.), common eel
4. *Tinca tinca* (L.), tench
5. *Scardinius erythropthalmus* (L.), rudd
6. *Rutilus rutilus* (L.), roach
7. *Perca fluviatilis* L., perch
8. *Gymnocephalus cernua* (L.), ruffe

AMPHIBIA (Holman, Clayden & Stuart, 1988; Holman, 1989)

1. *Triturus vulgaris* L., common newt
2. *Bufo bufo* (L.), common toad
3. *Rana arvalis* Nilsson, moor frog
4. *Rana 'esculenta'* L. or *Rana ridibunda* Pallas, edible frog or marsh frog
5. *Rana temporaria* L., common frog

REPTILIA (Holman, Clayden & Stuart, 1988; Holman, 1989)

1. *Anguis fragilis* L., slow worm
2. *Natrix natrix* (L.), grass snake
3. *Vipera berus* L., adder

AVES (C.J.O. Harrison, 1979)

1. cf. *Cygnus bewickii* Yarrell, Bewick swan
2. *Anser anser* (L.), grey-lag goose
3. *Anas platyrhynchos* L., mallard
4. *Anas penelope* L., wigeon
5. *Anas crecca* L., teal
6. *Netta rufina* (Pallas), red-crested pochard
7. *Aythya ferina* (L.), pochard
8. *Aythya fuligula* (L.), tufted duck
9. *Aix galericulata* L., mandarin
10. *Somateria gravipes* C.J.O. Harrison, extinct thick-legged eider
11. *Bucephala clangula* (L.), goldeneye
12. *Mergus albellus* L., smew
13. *Mergus serrator* L., red-breasted merganser
14. *Gallinula chloropus* (L.), moorhen
15. *Turdus ?merula* L., ?blackbird
16. *Sturnus ?vulgaris* L., ?starling
17. *Garulus ?glandarius* (L.), ?jay

MAMMALIA (sources include: Azzaroli, 1953; Hinton, 1908; 1911; 1926; Newton, 1882; 1909; Stuart, 1975; 1981; 1982; 1988; 1992a; in press; D.L. Harrison & Bates, 1984; Willemsen, 1990; Lister, in press a; in press b)

Chiroptera

1. *Nyctalus noctula* Schreber, noctule bat

Insectivora

2. *Erinaceus* cf. *europaeus* L., hedgehog
3. *Sorex runtonensis* Hinton, extinct shrew
4. *Sorex savini* Hinton, extinct shrew
5. *Neomys newtoni* Hinton, extinct water shrew
6. *Talpa europaea* L., common mole
7. *Talpa minor* Freudenberg, extinct mole
8. *Desmana moschata* (Pallas), Russian desman

Primates

9. *Macaca sylvanus* (L.), Barbary macaque

Lagomorpha

10. *Lepus* sp., a hare

Rodentia

11. *Sciurus whitei* Hinton, extinct squirrel[1]
12. *Trogontherium cuvieri* Fischer, extinct beaver-like rodent
13. *Castor fiber* L., beaver
14. *Cricetus cricetus* (L.), common hamster
15. small hamster, species not yet determined[2]
16. *Clethrionomys glareolus* Schreber, bank vole
17. *Pliomys episcopalis* Mehely, extinct vole
18. *Mimomys savini* Hinton, extinct water vole
19. *Pitymys arvaloides* Hinton, extinct pine vole
20. *Pitymys gregaloides* Hinton, extinct pine vole
21. *Microtus* cf. *arvalis* (Pallas), common vole
22. *Microtus oeconomus* (Pallas), northern vole
23. *Apodemus sylvaticus* (L.), wood mouse

Carnivora

24. *Canis lupus* L., wolf
25. *Ursus deningeri* von Reichenau, extinct bear
26. *Mustela nivalis* L., weasel
27. *Martes* sp., marten
28. *Pannonictis* sp., extinct mustelid
29. *Lutra simplicidens* Thenius, extinct otter
30. *Crocuta crocuta* (Erxleben), spotted hyaena
31. *Felis* cf. *lunensis* Martelli, extinct cat
32. undetermined large felid, probably lion or sabretooth

Table 3 (continued)

Proboscidea

33. *Mammuthus trogontherii* Pohlig, extinct elephant.

Perissodactyla

34. *Equus* sp. (caballine), a horse
35. *Dicerorhinus etruscus* (Falconer), extinct 'Etruscan' rhinoceros

Artiodactyla

36. *Sus scrofa* L., wild boar
37. *Megaloceros verticornis* (Dawkins), a giant deer
38. *Megaloceros savini* (Dawkins), a giant deer
39. *Dama dama* (L.), fallow deer
40. *Cervus elaphus* L., red deer
41. *Alces latifrons* Johnson, extinct elk (moose)
42. *Capreolus capreolus* (L.), roe deer
43. *Bison schoetensacki* Freudenberg, extinct bison

[1]Species recorded only from marine gravel overlying West Runton Freshwater Bed (probably reworked)

[2]Species recorded only from calcareous silts (bed g) at top of West Runton Freshwater Bed.

Only two other skeletons of this species are known, one from Germany (Sangerhausen), the other from Russia (near Azov).

The relatively narrow pelvic opening on the West Runton specimen indicates a male, while the fact that the last molars are in place, and moderately worn, indicates a mature individual. Preliminary estimates from the dimensions of the right ulna suggest an animal that in life reached perhaps 4 metres at the shoulder, and weighed 9 or 10 tonnes, nearly twice as heavy as an average modern adult male African elephant.

The fact that the West Runton elephant was found in the Cromerian stratotype, and in association with a wide range of other fossils, makes this a find of international importance.

The plant, mollusc and vertebrate fossils (Table 3) give a rather full picture of the environment in which the elephant lived. A slow-flowing river with aquatic vegetation was fringed by reedswamp and fen, while away from the river the valley was occupied by mixed oak forest and some herbaceous vegetation supporting a diverse vertebrate fauna (Stuart, 1982; 1992). The climate was temperate, probably much as it is today. A wide variety of plant food would have been available, including grasses, herbs, the leaves and twigs of various shrubs and trees, bark, and aquatic and waterside vegetation.

TAPHONOMY

The West Runton elephant had been exposed long enough for the skeleton to collapse and largely break up, although several vertebrae remained in articulation. Tooth marks and five coprolites (fossil droppings) found intermingled with the elephant bones indicate that hyaenas had fed on the carcass as it lay in shallow water in the river. The vertical separation of the *in situ* coprolites show that sediment was accumulating around the body as it lay in the water and that hyaenas fed on it on more than one occasion. Fossil evidence of hyaenas scavenging an elephant carcass has apparently not been recorded before. Modern spotted hyaenas *Crocuta crocuta* (Erxleben) in Africa have been observed to feed on carcasses in shallow water.

DATING THE CROMERIAN STAGE

An unexpected bonus from the find was the opportunity to determine for the first time an absolute date for the West Runton Freshwater Bed, and hence for the Cromerian Stage, using electron spin resonance (E.S.R.) dating. Elephant

teeth, because of their large size, give much better results than the teeth of other animals. J. Rink (Hamilton, Ontario) is currently working with small samples of tooth enamel from the West Runton elephant.

ACKNOWLEDGEMENTS

I am most grateful to J.D. Clayden, K. Johns, J. Lightwing, M. Hems, H. Hems, R. Sinclair and Norfolk Museums Service colleagues R.J. Driscoll, M. Warren, M. Davis and A.G. Irwin for all their hard work and expertise on site.

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A.M. Lister (University College, London) and H. van Essen confirmed the identification of the elephant taxon and provided much literature and discussion on fossil elephants. R. Croucher and A.P. Currant (Natural History Museum, London) provided valuable advice on conservation and excavation techniques.

Financial support for conservation, recording and display of the 1990-1992 finds has been generously provided by the Friends of the Norwich Museums.

Lastly I thank C. Wilson and B. McWilliams (Norfolk Museums Service) for their contnuing interest and support.

REFERENCES

AZZAROLI, A. 1953. The deer of the Weybourne Crag and Forest Bed of Norfolk. *Bulletin of the British Museum (Natural History) Geology.* **2**, 3-96.

DRISCOLL, R.J. & STUART, A.J. 1993. The West Runton elephant. *Earth Science Conservation* **32**, 9-11.

HARRISON, C.J.O. 1979. Birds of the Cromer Forest Bed series of the East Anglian Pleistocene. *Transactions of the Norfolk and Norwich naturalists Society* **24**, 277-286.

HARRISON, D. L. & BATES, P.J.J. 1984. Occurrence of Nyctalus noctula Schreber 1774 (Chiroptera; Vespertilionidae) in the Cromerian Interglacial of England. *Mammalia* **48**, 603-606.

HINTON, M.A.C. 1908. Note on the discovery of the bone of a monkey in the Norfolk Forest Bed. *Geological Magazine* **5**, 440-444.

HINTON, M.A.C. 1911. The British fossil shrews. *Geological Magazine* 8, 529-539.

HINTON, M.A.C. 1926. *Monograph of the Voles and Lemmings (Microtinae), Living and Extinct.* Volume I. (note volume II was never published). London: British Museum (Natural History).

HOLMAN, J.A., CLAYDEN, J.D. & STUART, A.J. 1988. Herpetofauna of the West Runton Freshwater Bed (Middle Pleistocene; Cromerian Interglacial), West Runton, Norfolk. *Bulletin of the Geological Society of Norfolk* **38**, 121-136.

HOLMAN, J.A. 1989. Additional herpetological records from the Middle Pleistocene (Cromerian Interglacial) Freshwater Bed, West Runton, Norfolk. *British Herpetological Society Bulletin* **27**, 9-12.

LISTER, A.M. (in press a). The stratigraphical significance of large-mammal remains from the Cromer Forest-bed Formation. In: Turner, C. (ed.). *The Early Middle Pleistocene of Europe.* Balkema: Rotterdam.

LISTER, A.M. (in press b). The stratigraphical significance of deer remains in the Cromer Forest-bed Formation. *Journal of Quaternary Science.*

LISTER, A.M. (in press c). Evolutionary history of the mammoth lineage in Eurasia. *Palaeontology*

MCWILLIAMS, B. 1967. Fossil Vertebrates of the Cromer Forest Bed in *Norwich Castle Museum.* Norwich: City of Norwich Museums.

MEIJER, T. & PREECE, R.C. (in press). Malacological data relating to the stratigraphic position of the Cromerian. In: Turner, C. (ed.). *The Early Middle Pleistocene of Europe.* Rotterdam: Balkema

NEWTON, E.T. 1882. The vertebrata of the Forest Bed Series of Norfolk and Suffolk. *Memoir of the Geological Survey of the United Kingdom.*

NEWTON, E.T. 1909. Hamster from the Norfolk Forest Bed. *Geological Magazine* **6**, 110-113.

OWEN, R. 1846. *A History of British Fossil Mammals and Birds* London:Van Voorst.

REID, C. 1882. The geology of the country around Cromer. *Memoir of the Geological Survey of the United Kingdom.*

REID, C. 1890. The Pliocene deposits of Britain. *Memoir of the Geological Survey of England and Wales.*

STINTON, F. 1985. Quaternary fish otoliths. *Proceedings of the Geologists' Association* **96**, 199-215.

STUART, A.J. 1975. The vertebrate fauna of the type Cromerian. *Boreas* 4, 63-76.

STUART, A.J. 1981. A comparison of the Middle Pleistocene mammalian faunas of Voigtstedt (Thuringia, German Democratic Republic) and West Runton (Norfolk, England). *Quartärpaläontologie Berlin* 4, 155-163.

STUART, A.J. 1982. *Pleistocene Vertebrates in the British Isles.* London: Longman.

STUART, A.J. 1988. The vertebrate faunas from West Runton (Crag and Freshwater Bed). In: Gibbard, P.L. & Zalasiewicz, J.A (eds.) 1988. *Pliocene- Middle Pleistocene of East Anglia.* Field Guide. Cambridge: Quaternary Research Association, pp. 152-157.

STUART, A.J. 1992a. The Pleistocene vertebrate faunas of West Runton, Norfolk, England. *Cranium* **9** (2), 77-84.

STUART, A.J. 1992b. Fossil elephant skeleton from the Cromer Forest Bed. *Transactions of the Norfolk and Norwich naturalists Society*, 29(3), 196-198.

STUART, A.J. (in press). Vertebrate faunas from the early Middle Pleistocene of East Anglia. In: Turner, C. (ed.). *The Early Middle Pleistocene of Europe.* Rotterdam.: Balkema.

WEST, R.G. 1980. *The Pre-Glacial Pleistocene of the Norfolk and Suffolk Coasts.* Cambridge: Cambridge University Press.

WILLEMSEN, G.F. 1990. *A Revision of the Pliocene and Quaternary Lutrinae from Europe.* Ph.D. thesis, University of Utrecht.

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The Geological Society of Norfolk exists to promote the study and knowledge of geology, particularly in East Anglia, and holds monthly meetings throughout the year.

Visitors are welcome to attend the meeting and may apply for membership of the society. For further details write to the Secretary, Geological Society of Norfolk, Castle Museum, Norwich NR1 3JU.

Copies of the Bulletin may be obtained from the Secretary at the address given above; it is issued free to members.

The illustration on the front cover is taken from figure 4 of K. Hiscock's article in this issue of the Bulletin. It is a hydrogeology map of north east Norfolk, depicting groundwater conditions measured in May 1981.

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BULLETIN OF THE GEOLOGICAL SOCIETY OF NORFOLK

(FOR ARTICLES ON THE GEOLOGY OF EAST ANGLIA)

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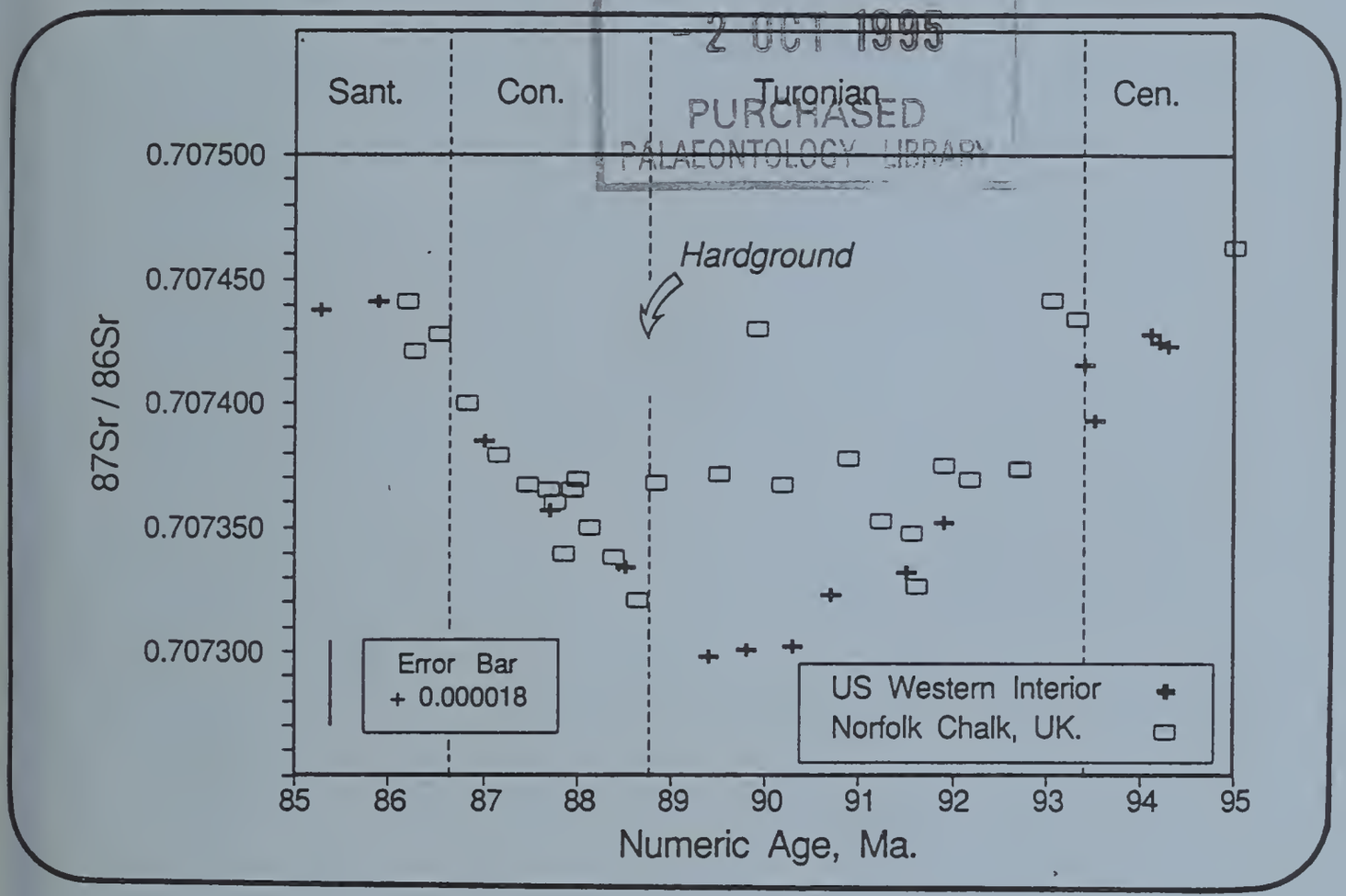

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Strontium Isotopes
of the Norfolk Chalk

Carbonate mineralogy
of Holkham Lake

BULLETIN OF THE GEOLOGICAL SOCIETY OF NORFOLK

No. 42 (for 1992) Published 1995

Editor: Julian E. Andrews

School of Environmental Sciences,
University of East Anglia,
Norwich NR4 7TJ

Telephone 01603 592536
FAX 01603 507719
E-mail J.Andrews@uea.ac.uk

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EDITORIAL

Here at last is Bulletin No. 42. I apologise for the long delay in publication of this issue, which like earlier issues has had to await the accumulation of sufficient material.

Bulletin 42 has a strong geochemical flavour. John McArthur's paper on strontium isotope geochemistry of the Norfolk chalk demonstrates a novel approach to stratigraphic correlation and highlights the importance of the Norfolk chalk in worldwide correlation of the Cretaceous. In contrast, David Lucas' unusual paper on carbonate mineralogy in Holkham Lake suggests that the unexpected world renown of the lake may be erroneous.

I am still very short of material for future issues and welcome the submission of papers on any aspect of East Anglian geology. My intention is to publish a series of 50 page Bulletins in fairly rapid succession to catch up on the publication schedule.

INSTRUCTIONS TO AUTHORS

If possible, contributors should submit manuscripts as word-processor print out accompanied by a disk copy. We can handle most word-processing formats although PC Word, WordPerfect or ASCII files are preferred. In addition we accept typewritten copy and will consider legible handwritten material.

It is important that the style of the paper, in terms of overall format, capitalisation, punctuation, etc. conforms as strictly as possible to that used in Vol. 41 of the Bulletin. Titles and first order headings should be capitalised, centred and in bold print. Second order headings should be centred, bold and lower case. Text should be 1½ line spaced. All measurements should be given in metric units.

References should be arranged alphabetically in the following style.

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STEERS, J.A. 1960. Physiography and evolution: the physiography and evolution of Scolt Head Island. In: Steers, J.D. (ed.) *Scolt Head Island* (2nd ed.), 12-66, Heffer, Cambridge.

BLACK, R.M. 1988. *The Elements of Palaeontology*. 2nd Ed., Cambridge University Press, Cambridge. 404pp.

Illustrations should be drawn with thin dense black ink lines. Thick lines, close stipple or patches of solid black should be avoided as these spread in printing. Original illustrations should, before reproduction, be not more than **175mm by 255mm**. Full use should be made of the first (horizontal) dimension which corresponds to the width of print on the page, but the second (vertical) dimension is an upper limit only. Half tone photographic plates are acceptable when their use is warranted by the subject matter, provided the originals exhibit good contrast.

The editors welcome original research papers, notes or comments, and review articles relevant to the geology of **East Anglia** as a whole, and do not restrict consideration to articles covering Norfolk alone. All papers are independently refereed by at least one reviewer.

EVOLUTION OF MARINE $^{87}Sr/^{86}Sr$ DURING THE CENOMANIAN - EARLY MAASTRICHTIAN, DETERMINED FROM THE CHALK OF NORFOLK.

J.M. McArthur

Research School of Geological and Geophysical Sciences,
Birkbeck College and University College London,
Gower Street, London WC1E 6BT.

ABSTRACT

The Chalk rock, deep beneath the village of Trunch in northeastern Norfolk, is the thickest on the UK mainland. It comprises a very thick and most complete Campanian Chalk sequences, as well as a substantial thickness of Santonian to Cenomanian Chalk. The strontium contained within the chalk preserves a record of how the strontium isotopic ratio (see glossary) of Late Cretaceous seawater varied during the period in which the Chalk was deposited. The variations in $^{87}Sr/^{86}Sr$ provide a standard curve that permits comparison to the Trunch curve of the $^{87}Sr/^{86}Sr$ of other strata worldwide, and therefore permits correlation to the Chalk of Norfolk, from localities world-wide, without the use of fossils or magnetostratigraphy. For the Santonian and Campanian stages, where the curve has its steepest slope and is best defined, correlation can be achieved with a temporal resolution of ± 0.5 myr, and a stratigraphic resolution of ± 14m of section.

INTRODUCTION

The use of Sr isotopes to date marine minerals, a technique known as Sr isotope stratigraphy, dates from a suggestion of Wickman (1948) that the $^{87}Sr/^{86}Sr$ of Sr dissolved in seawater should increase with the passage of time because the oceans are continuously being supplied with the products of continental weathering, which include Sr with an $^{87}Sr/^{86}Sr$ greater than that of marine Sr. Measurement of the $^{87}Sr/^{86}Sr$ in marine minerals should therefore allow the time of their formation to be determined. The principle of this

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method of dating and correlation is shown in figure 1; profiles of $^{87}Sr/^{86}Sr$ against stratigraphic level are determined for separate rock sequences. Levels which have the same $^{87}Sr/^{86}Sr$ value must have formed at the same time and so correlate precisely, because $^{87}Sr/^{86}Sr$ in the worlds oceans is globally homogenous on time scales greater than about 1000 years. If a numerical calibration can be placed on the biostratigraphy in either sequence, and hence on the stratigraphic levels, $^{87}Sr/^{86}Sr$ can be used in both to determine numerical age at any level. Since Wickman's suggestion, the measurement of $^{87}Sr/^{86}Sr$ in marine carbonates of known age (biostratigraphic and numerical) has been used to document the temporal evolution of marine $^{87}Sr/^{86}Sr$ during much of Phanerozoic time and to demonstrate that this method for dating and correlating marine sediments has great potential (see McArthur, 1994b, for a review). Curves of $^{87}Sr/^{86}Sr$ against numeric age that are of an accuracy sufficient for useful stratigraphy have now been defined for the Neogene (Hodell et al., 1989, 1990; Hodell, 1991; Hodell and Woodruff, 1994; Miller et al., 1991; Paytan et al., 1993 Oslick et al. 1994; Farrell et al., 1995), parts of the Palaeogene (Hess et al., 1986, 1989; Miller et al., 1988), the Late Cretaceous (McArthur et al., 1993a,b, 1994a; Sugarman et al., 1995) and the Jurassic and Early Cretaceous (Jones et al., 1994a,b).

As part of this worldwide effort to provide a standard curve for Phanerozoic time, $^{87}Sr/^{86}Sr$ has been profiled through the thick sequence of Upper Cretaceous Chalk recovered from the stratigraphic borehole drilled near the village of Trunch, in northeastern Norfolk. Analysis of $^{87}Sr/^{86}Sr$ in the samples recovered from the borehole provides a good record of variations in the $^{87}Sr/^{86}Sr$ of marine Sr during the Cenomanian - early Maastrichtian. The isotopic record provides a quantitative template with which to correlate Upper Cretaceous strata of Norfolk with strata world-wide, and against which to match and integrate diverse stratigraphic schemes *via* common isotopic signatures. A preliminary description of the profile was given in McArthur et al. (1993a) but, since then, additional material has been analysed and $^{87}Sr/^{86}Sr$ profiles in sequences in Germany and the USA have become available (McArthur et al., 1993b, 1994a), thereby allowing a better interpretation of the Trunch data to be made. This paper presents this new data and the improved interpretations.

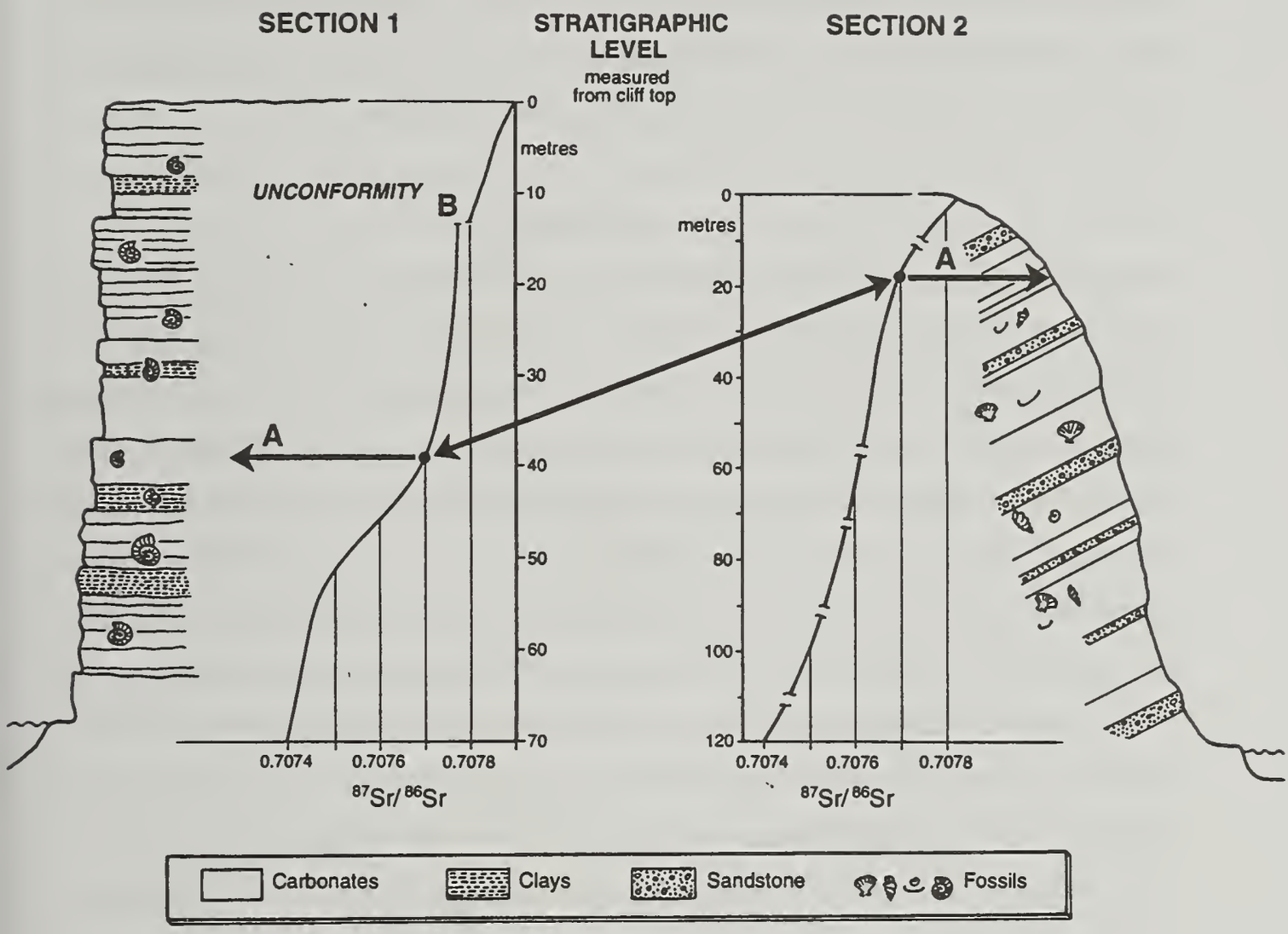

Fig. 1. Correlating rocks with Sr isotopes. The $^{87}Sr/^{86}Sr$ is profiled through separate sequences. Stratigraphic levels in each which have the same $^{87}Sr/^{86}Sr$ must have formed at the same time and therefore correlate, *e.g.* at level A. Breaks in the $^{87}Sr/^{86}Sr$ profiles *e.g.* at B, reveal breaks in sedimentation. Biogenic carbonate is a suitable material for the determination of $^{87}Sr/^{86}Sr$ as it contains many hundreds of parts per million of Sr.

THE ENGLISH CHALK AT TRUNCH

The British Geological Survey (then the Institute of Geological Sciences) borehole, drilled near Trunch in Norfolk (Fig. 2), cored much of the most complete development of Chalk onshore in the UK. It penetrated 468m of Cenomanian - lower Maastrichtian Chalk, for which the lithostratigraphy, and biostratigraphy are well documented (Gallois and Morter, 1975; Morter and Gallois, 1979; Burnett, 1988, 1990; Wood et al., 1994).

Lithology

Lithological division of the section follows Wood et al. (1994), Rawson et al. (1978) and Peake and Hancock (1961). The Chalk of Norfolk comprises mostly calcareous nannofossils with subsidiary quantities of foraminifera, calcispheres and macrofossil debris, mostly bivalves, echinoderms and bryozoa (Hancock, 1975; Bromley, 1979). Non-carbonate material, predominantly clay minerals (smectite and illite) and quartz, constitutes 30% to 40% of the Lower Chalk, but only 1% to 3% of the Middle and Upper Chalk (Hancock, 1975; Bath and Edmunds, 1981). The Upper Chalk of Norfolk is generally poorly cemented and retains up to 40% porosity, having "largely resisted recrystallisation and lithification" (Bath and Edmunds, 1981). The proportion of cement, present as overgrowth, is low and obscures only the fine detail of coccolith structure (Burnett, 1990). Overgrowths act as a weak cement by bridging coccolith contacts. A small amount of microspar in voids is randomly present (Hancock, 1975). The Upper Chalk is rich in flint, which occurs in nodular, tabulate, and paramoudra forms. In the Lower and Middle Chalk of the Trunch borehole, localised diagenesis has formed common nodular chalks and hardgrounds. Flints occur at two horizons within the middle Chalk and are absent from the Lower Chalk. Celestite was noted at 314m, 332m and 370m (Morter and Gallois, 1979) and may occur at other levels; below 100m concentrations of Sr in pore-water were in equilibrium with celestite (25 ± 5 mg l^{-1}, Bath and Edmunds, 1981), which suggests this mineral may be ubiquitous below 100m, although largely unnoticed.

Lithostratigraphy

The succession at Trunch shows many similarities to outcrops in Norfolk and Lincolnshire, and within it can be recognised many regional marker beds (marls, hardgrounds, fossil beds), the most important of which are shown on figure 2. The Lower Chalk (11.7m) rests

non-sequentially on Albian Red Chalk and comprises of condensed marly nodular chalks which contain abundant inoceramid debris and many hardgrounds and omission surfaces. The Totternhoe Stone is recognised between 505.2 and 506.3m. The Middle Chalk (31.2m) is nodular and contains abundant inoceramid debris in its lower part; the upper part contains distinctive regional marker marls (Grasby, Barton, Melton Ross, Riby, Lower Deepdale), and nodular and tabular flints. The Upper Chalk (425m) also contains distinctive regional marker marls (Ulceby, North Ormsby) as well as flints throughout. Within the Upper Chalk the lithological divisions of Sidestrand, Paramoudra, Beeston, Weybourne/Eaton, and Basal Mucronata Chalk can be recognised (Fig. 2). Two well-developed hardgrounds occur at 209m and 432m. The lower is probably the lateral equivalent of the "Navigation Hardground" of southern England (Wood et al., 1994). Stylolitic marly partings and omission surfaces are common between 400 and 470m. The section 432m to 470m contains several minor hardgrounds as well as numerous omission surfaces.

Between the Coniacian/Turonian boundary (88.7 ± 1 Ma; see section on numerical ages) and the Maastrichtian/Campanian boundary (71.3 ± 1 Ma), about 370m of Chalk were deposited with only one major identifiable break in sedimentation, the hardground at 209m. This sequence therefore represents a reasonably continuous sedimentation rate (present compaction) of between 19 and 24m myr^{-1}. Below the Coniacian, hardgrounds and omission surfaces make the meaning of such calculations unclear, so they are not made.

Macrofossil Biostratigraphy

The macrofossil zonation shown in figure 2 is based on Wood et al. (1994) and follows Peake and Hancock (1961) and Rawson et al. (1978). Stage boundaries were recognised by the following criteria, following Birkelund et al. (1984):

The Albian/Cenomanian boundary is placed at 512.2m, at an unconformity taken to be equivalent to the basal Paradoxica Bed elsewhere, which has yielded Cenomanian fossils.
The Cenomanian/Turonian boundary is placed at 500.1m, at the level of first occurrence of inoceramid bivalve *Mytiloides*.

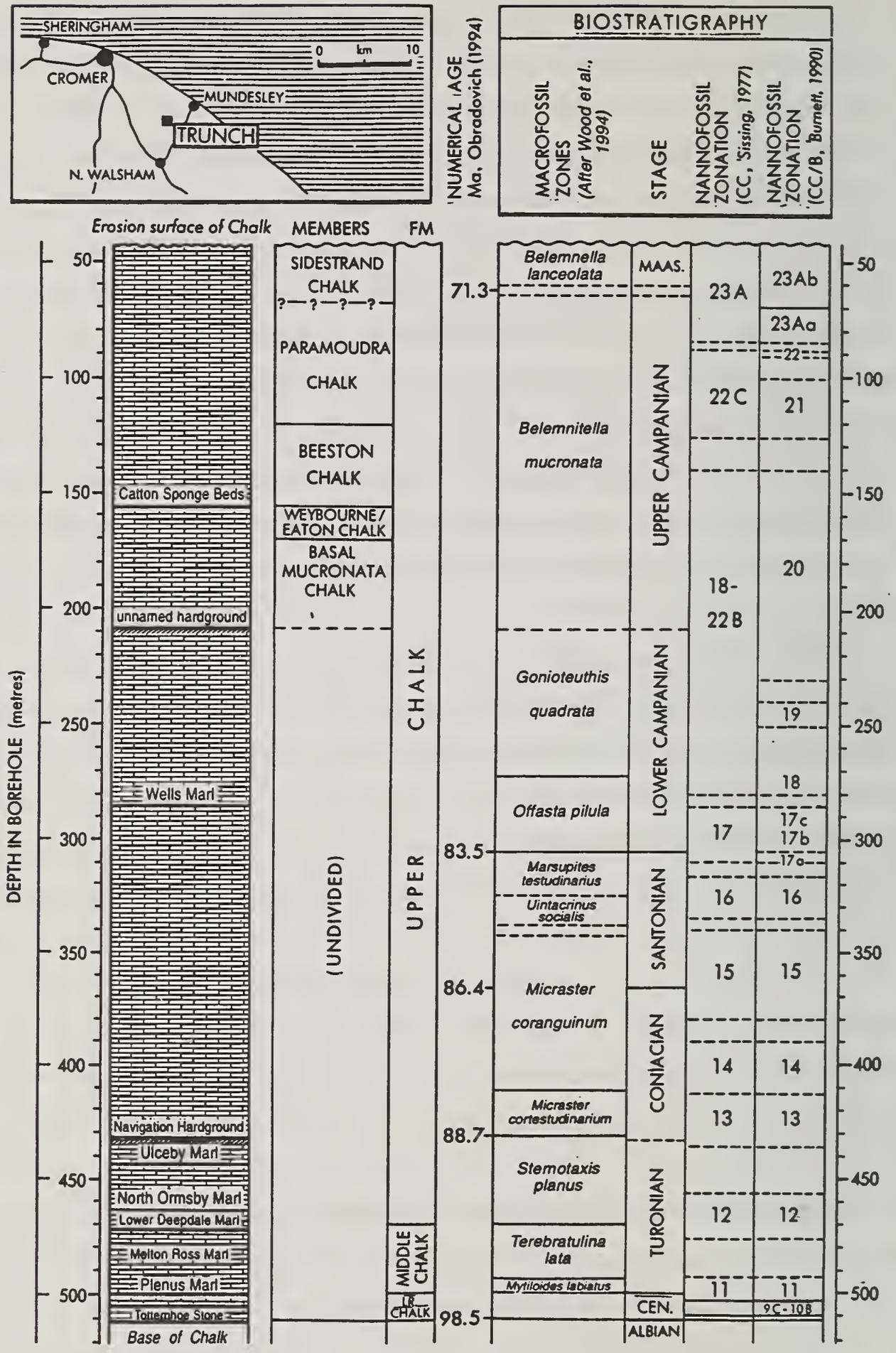

Fig. 2. Location of the Trunch borehole, and the stratigraphy of the sequence recovered (after Morter and Gallois, 1979; Wood et al., 1994).

The Turonian/Coniacian boundary is placed at 432.0m, which is the base of the England (Mortimore, 1986).

The Coniacian/Santonian boundary is placed at 365.8m, at which level the inoceramid *Cladoceramus undulatoplicatus* (Roemer) first occurs.

The Santonian/Campanian boundary is placed at 307.4m, at the level of last occurrence of the pelagic crinoid *Marsupites testudinarius* (Schlotheim).

The Campanian/Maastrichtian boundary is placed at 62.5m, at the level of first occurrence of *Belemnella* sp. in correlative beds on the Norfolk coast. On foraminiferal evidence it is placed at 61m by Wood et al. (1994).

The uncertainty in placing macrofossil boundaries within the core is estimated to be no more than ± 3m, which is equivalent in time to a period of no more than ± 0.12 myr.

Nannofossil Biostratigraphy.

The calcareous nannofossil zonation of the borehole (Fig. 2; Burnett, 1988) is based on the standard calcareous nannofossil zonation scheme (CC zones) of Sissingh (1977), as amended by Perch-Nielsen (1979; 1985). The nannofossil zonation has been further refined by the definition of Boreal subzones (Fig. 2; Burnett, 1990) which are also recognised in the Late Cretaceous standard sections in northern Germany (Lägerdorf and Kronsmoor). Nannofossil boundaries have been located with variable accuracy of between ± 11m (CC12/CC13) and ± 1.5m (CC13/CC14). These uncertainties are determined mostly by the sampling interval and are shown in figure 2.

SAMPLES ANALYSED

Values of $^{87}Sr/^{86}Sr$ have been determined for nannofossil chalks and fragments of macrofossils taken from throughout the 468m of chalk penetrated by the Trunch borehole. The nannofossil samples were white chalks above 500m, and grey marls below 500m, with varying contents of $CaCO_3$ (Table 1). Samples from depths of less than 400m were soft-to-moderately cemented; those below were noticeably harder, particularly below 430m. The macrofossils were fragments of inoceramids, echinoids, belemnites and

Table 1. Isotopic and element data for samples of nannofossil chalk and macrofossil fragments from the Trunch borehole.

Stage	Sample Number	Sample Description	Depth metres	87Sr/86Sr	Error	Mean 87Sr/86Sr	Del 13C	Del 18O	CaCO3 %	Sr ppm
MAASTRICH	1		47	0.707785	8	0.707785	1.85	-1.70	96.1	580
				0.707785	9					
	BDJ 21	Belemnite	48.6	0.707731	7	0.707739	0.79	-0.14	80.4	840
				0.707748	8					
	3		50	0.707773	9	0.707779	1.81	-1.53	93.0	740
				0.707785	7					
	4		58	0.707787	7	0.707787	1.83	-2.04	92.0	480
	5		60	0.707773	9	0.707773	1.85	-1.91		
	Maastrichtian - Campanian Boundary at 62.5m, 71.3 Ma									
CAMPANIAN	BDJ 82	*Cretirhynchia sp.*	64.2	0.707749	8	0.707749			100.0	855
	8		68	0.707751	8	0.707751	1.77	-2.17	99.8	640
	9		71	0.707760	8	0.707760				
	BDJ 101	Brachiopod	71.1	0.707728	8	0.707728				
	BDJ 113	Brachiopod	71.5	0.707713	6	0.707713				
	10		81	0.707750	8	0.707750	1.96	-2.05	94.8	610
	BDJ 148	Inoceramid	82.9	0.707690	10	0.707690				
	BDJ 171	Belemnite	84.8	0.707698	8	0.707698			93.9	1320
	BDJ 172	Belemnite	84.9	0.707720	9	0.707701				
				0.707681	9					
	BDJ 177	Belemnite	85.2	0.707701	9	0.707701				
	BDJ 227	Inoceramid	88.8	0.707721	8	0.707708				
				0.707694	10					
	BDJ 245	Inoceramid	90.2	0.707694	8	0.707694			96.8	360
	11		91	0.707732	12	0.707732	1.83	-1.84	95.0	835
	BDJ 415	Belemnite	100.2	0.707675	7	0.707675	2.48	-0.19	95.5	1170
		Belemnite		0.707673	9	0.707673				
	12		101				1.88	-1.84		
	T(M)3		101	0.707702	8	0.707702	1.98	-1.89	96.8	830
	13		111	0.707692	7	0.707692	1.95	-1.75	92.5	765
		Carneithyris sp.	126	0.707637	9	0.707637	2.27	-1.19	89.8	755
	16		140	0.707663	14	0.707663	1.97	-2.35	95.2	760
		Belemnite	148	0.707622	8	0.707622			99.1	1180
	18		160	0.707646	8	0.707646	1.95	-2.20	97.3	590
		Irreg. Echinoid	175	0.707592	9	0.707592			98.8	385
	20		180	0.707602	9	0.707602	1.96	-2.23	97.3	775
	21		191	0.707582	10	0.707582	2.40	-1.68	97.7	825
		Brachiopod	200	0.707557	12	0.707557			99.1	805
		Belemnite	210	0.707555	8	0.707555			99.6	1310
	23		211	0.707568	7	0.707568	2.34	-2.04	98.6	830
	24		221	0.707550	8	0.707550	2.36	-2.06	93.2	730
	4002		226	0.707584	8	0.707584			93.4	875
		Brachiopod	226	0.707544	9	0.707544				
		Irreg. Echinoid	226	0.707569	9	0.707569	2.32	-1.17	94.5	435
		Bourgueticrinus	229	0.707601	11	0.707601			95.4	295
	25		231	0.707571	11	0.707571	2.29	-2.38	93.9	805
	26		240	0.707581	11	0.707581	2.28	-2.54	94.6	800
		Belemnite	249	0.707528	8	0.707528			63.2	890
	27		250	0.707536	7	0.707536	2.16	-2.58	94.3	770
	28		260	0.707542	7	0.707542	2.31	-2.52		
	5777		275	0.707540	11	0.707540			97.0	880
		Oyster	275	0.707522	9	0.707522			97.0	730
	30		280	0.707544	9	0.707531	2.22	-3.02	94.8	785
				0.707519	8					
	32		300	0.707506	13	0.707506	2.62	-2.55	93.2	890
		Inoceramid	300	0.707472	9	0.707472	2.66	-0.90	23.9	6950
	Santonian - Campanian Boundary at 307.4m, 83.5 Ma									
SANTONIAN	33		310	0.707527	8	0.707527	2.27	-3.29	98.8	1040
	34		320	0.707486	10	0.707495			98.8	960
				0.707504	9					
	35		330	0.707497	9	0.707486	2.36	-2.74	97.7	860
				0.707476	9					
	37		350	0.707471	7	0.707471	2.49	-2.59	97.5	715
		Inoceramid	352	0.707451	8	0.707451			26.3	110
	38		360	0.707448	9	0.707456			98.9	800
				0.707456	8					
				0.707457	17					
				0.707461	8					

				0.707462	7					
				0.707464	8					
		Coniacian - Santonian Boundary at 365.8m. 86.3 Ma								
C		39		370	0.707444	9	0.70743	1.86	-2.45	99.3	730
					0.707417	11					
O		40		380	0.707427	8	0.707409	2.56	-2.67	99.1	800
					0.707410	17					
N					0.707390	10					
		41		390	0.707394	11	0.707394	2.38	-2.64	98.0	705
I		42		396				2.52	-2.70		
		43		397	0.707395	7	0.707395	2.71	-2.88	97.9	690
A		44		399	0.707390	13	0.707390	2.68	-3.44	98.9	560
			Inoceramid	402	0.707370	7	0.707370			29.8	75
C		47		405	0.707395	8	0.707395	2.41	-2.42	99.1	590
		48		407	0.707399	8	0.707399	2.16	-2.35	99.5	590
I		50		411	0.707382	9	0.707381	2.11	-2.78	98.8	700
					0.707379	9					
A		54		419	0.707368	9	0.707368	2.18	-2.79	98.9	650
		58		427	0.707351	8	0.707351				
N		60		431				1.86	-2.89		
		Turonian - Coniacian boundary at 432.5m, 88.7 Ma									
T		61		433	0.707398	7	0.707398	1.92	-2.81	99.1	580
		63		443	0.707402	9		1.78	-3.85	97.3	650
U					0.707401	11	0.707401				
					0.707401	8					
R			Brachiopod	449	0.707430	9	0.707430			99.1	460
		65		453	0.707397	9	0.707397	1.82	-3.81	97.9	545
O		67		463	0.707408	16	0.707408	2.01	-3.30	96.3	520
		68		468	0.707383	9	0.707383	1.82	-2.53	96.6	810
N		69		473	0.707364	7	0.707378	2.00	-3.15	97.9	630
					0.707392	7					
I			Inoceramid	474	0.707326	15	0.707326			94.8	646
		70		478	0.707405	9	0.707405	1.93	-3.67	97.1	690
A		71		482	0.707399	9	0.707399	2.24	-2.51	98.4	600
		72		490	0.707404	9	0.707405	2.24	-3.64	97.1	500
N					0.707406	10					
		73		495	0.707472	8	0.707472	2.78	-3.49	97.1	315
		74		499	0.707457	9	0.707463	3.36	-2.47	98.6	325
					0.707471	10					
		Cenomanian - Turonian boundary at 500.1m, 93.4 Ma									
C											
E		77		504	0.707493	8	0.707493	2.76	-3.31	92.3	670
N		79		506	0.707514	8	0.707502	2.23	-2.66	88.0	700
O					0.707489	9					
M		81		508	0.707504	16	0.707504	1.97	-2.13	93.8	650
A		83		510	0.707515	9	0.707515	1.79	-3.05	95.0	655
N		84		511	0.707495	9	0.707495	1.83	-2.92	87.7	630
		Albian - Cenomanian boundary at 512.5m, 98.5 Ma									
ALBI		87		513	0.707525	9	0.707525	1.64	-3.34	91.8	735

brachiopods; some were partially silicified and so contained less than 100% $CaCO_3$ (Table 1).

ANALYTICAL METHODS AND RESULTS

Macrofossil fragments were washed under the tap, coarsely fragmented with a pestle and mortar, ultrasonically cleaned in ultra-pure water, briefly immersed in dilute acid (5% HCl) to remove surface deposits, and then rinsed in ultra-pure water before drying. Handpicked fragments were then dissolved in 20% HCl. After centrifugation, 2 ml aliquots of solution were evaporated to dryness with 50% HCl for subsequent separation of Sr.

Nannofossil samples (100 ± 10mg) were ultrasonically disaggregated in ultra-pure water and partially dissolved by the addition of 20ml of ultra-pure 100% acetic acid, in order to remove surface deposits and surficial diagenetic cements and displace any contaminant Sr on exchangeable sites, e.g. clays. After centrifugation the supernatant was discarded. A further 3 ml of ultra-pure water and 20ml of ultra-pure 100% acetic acid were then added to dissolve a further 15% of the sample; partial dissolution ensured that the final pH of the solution was high thereby avoiding continued acid attack on residual material. After reaction the supernatant was centrifuged twice and 2 ml evaporated to dryness with 50% HCl.

Following preparation, Sr was separated by standard methods of ion-exchange chromatography and $^{87}Sr/^{86}Sr$ was determined with a VG-354 mass spectrometer (Thirlwall, 1991). To correct for the fact that isotopic fractionation occurs during mass-spectrometric analysis, all data were adjusted to have an $^{86}Sr/^{88}Sr$ ratio of 0.1194. To avoid interlaboratory bias, all data were also adjusted so that the $^{87}Sr/^{86}Sr$ of the laboratory standard, SRM987, was 0.710248. The analytical error of the methods was ± 18 x 10^{-6}. Replicates of 13 samples were run during the period of analysis and the data are shown in Table 1. Procedural blanks were insignificant (< 2 ng of Sr, with an $^{87}Sr/^{86}Sr$ close to 0.71). Concentrations of Sr and Ca were measured with a precision of <5% using atomic absorption spectrometry after dissolving samples in 10% HCl. The analytical results are given in Table 1, where Ca is reported as an equivalent percentage of $CaCO_3$. Figure 2 shows the stratigraphy of the Trunch sequence, figure 3 shows $^{87}Sr/^{86}Sr$ against depth in the borehole, and figure 4 shows $^{87}Sr/^{86}Sr$ plotted against numeric age.

DISCUSSION

The Late Cretaceous Sr-Isotope Curve

The Trunch profiles of $^{87}Sr/^{86}Sr$ show trends that can be reliably interpreted in the light of $^{87}Sr/^{86}Sr$ profiles through sequences in Germany and the USA (McArthur et al., 1993b, 1994a). Figures 3 and 4 show the evolution of $^{87}Sr/^{86}Sr$ as revealed in the Trunch borehole. For reasons given below, the data for parts of the sequence around 432-470m and 225m (A and B, figure 3) are considered to be aberrant and not to represent the true evolution of marine $^{87}Sr/^{86}Sr$ at these levels.

Variation of $^{87}Sr / ^{86}Sr$ with Depth

Three distinct parts can be seen in the Trunch profile of $^{87}Sr/^{86}Sr$ against depth (Fig. 3). In the deepest part, between the base of the Chalk at 512.2m and a level of 470m, $^{87}Sr/^{86}Sr$ decreases upward through the condensed sequence of Cenomanian and lower Turonian strata that contains many minor hardgrounds and omission surfaces.

The second part of the profile occurs between 470m and a very strong hardground at 432m (the "Navigation Hardground equivalent"). This flat part of the profile is defined by five nannofossil samples which have similar $^{87}Sr/^{86}Sr$ values of close to 0.70740 and one fossil sample with a higher ratio (A on Fig. 3). These samples have elevated $^{87}Sr/^{86}Sr$ compared to that in material of the same age from the U.S. western interior (Fig. 5). The elevated $^{87}Sr/^{86}Sr$ that occur for 38m below the hardground at 432m clearly results from diagenesis associated with the formation of this very prominent hardground (the "Navigation Hardground equivalent"). The many minor hardgrounds and omission surfaces below 470m, and the less numerous one above 432m, have not disturbed $^{87}Sr/^{86}Sr$ values much (Fig. 5).

The third part of the profile occurs above 432m, through most of the Coniacian and younger strata, where the $^{87}Sr/^{86}Sr$ increases steadily to the top of the chalk sequence, which terminates at 44m, some 18m above the Campanian/Maastrichtian boundary. Above 432m the sequence is more complete than below it; minor omission surfaces are common between 400m and 432m but their formation appears not to have affected $^{87}Sr/^{86}Sr$ (Fig. 5). Between 226m and 240m, five samples plot above the trend of the data (B on Fig. 3). These elevated $^{87}Sr/^{86}Sr$ are probably caused by diagenesis associated with a major

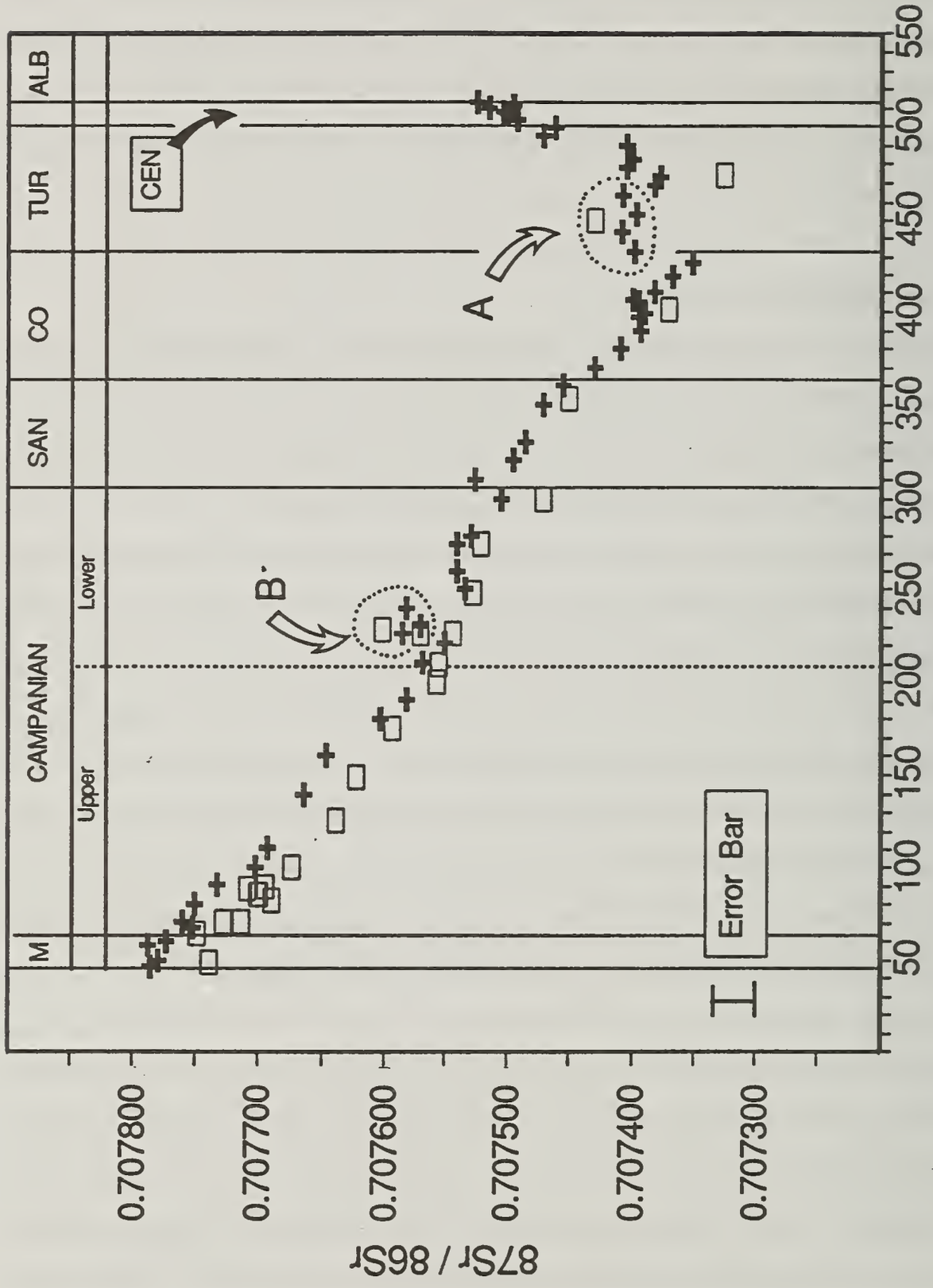

Fig. 3. $^{87}Sr/^{86}Sr$ with depth for the Trunch Borehole, Norfolk, UK.

hardground that occurs at 209m (the only one above 432m), as neither a major inflexion, nor such anomalous data, are seen in a profile of $^{87}Sr/^{86}Sr$ through the Chalk of Germany, in which $^{87}Sr/^{86}Sr$ is even less altered than it is in the Norfolk Chalk (McArthur et al., 1993b).

Variation of $^{87}Sr/^{86}Sr$ with Numeric Age

In figure 4, $^{87}Sr/^{86}Sr$ is profiled against numerical age, which have been assigned using the dates for stage boundaries given by Obradovich (1993) and interpolating ages between stage boundaries assuming a constant rate of sedimentation within each stage. A quasi-linear increase in $^{87}Sr/^{86}Sr$ with time occurs through the Campanian of the German Chalk (McArthur et al., 1993b), a fact that suggest the rate of evolution with time of marine $^{87}Sr/^{86}Sr$ varied little during that period. Assigning numeric age on the basis of $^{87}Sr/^{86}Sr$ is therefore possible, a procedure that would allow variations in sedimentation rate through the sequence to be established. This exercise is best left until the apparent linear increase with time of $^{87}Sr/^{86}Sr$ has been validated by examination of other sequences. Nevertheless, it is worth noting that, though the rate of increase of $^{87}Sr/^{86}Sr$ with stratigraphic level approximates to linearity, the rate of increase per metre of sediment is slightly lower in the Lower Campanian than either above or below this level. This is ascribed to a slightly faster rate of sedimentation in the Lower Campanian. No allowance has been made for such variation when assigning numeric age.

Preservation

Through those parts of the sequence in which $^{87}Sr/^{86}Sr$ is not diagenetically altered, values of $^{87}Sr/^{86}Sr$ for macrofossils are lower by about 30×10^{-6} than they are in nannofossil chalks from the same level (Table 1; Fig. 3), apart from one sample at 450m. Macrofossil preservation is variable through the sequence. Some samples, for example the inoceramid at 474m and the *Cretirhynchia* sp. at 64m, showed excellent preservation of the fine shell-structure, whilst others have been replaced to varying degrees by silica, for example, the inoceramids at 300m and 352m (Table 1). Nevertheless, the macrofossil data probably reflect original $^{87}Sr/^{86}Sr$ more closely than do the nannofossil chalks even though nannofossils appear only a little overgrown under the SEM and this diagenetic calcite does

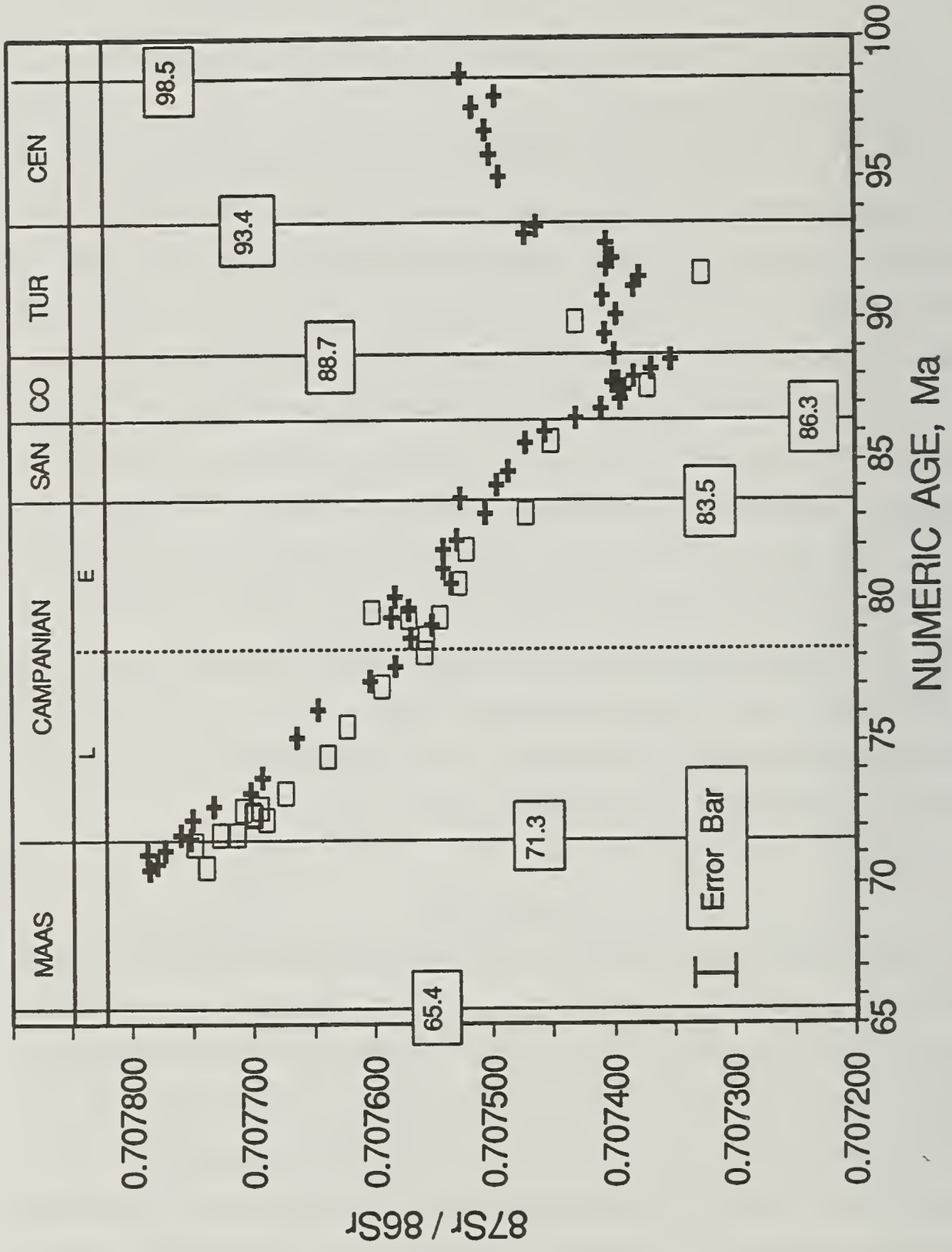

Fig. 4. $^{87}Sr/^{86}Sr$ with numeric age for the Trunch Borehole, Norfolk, UK.

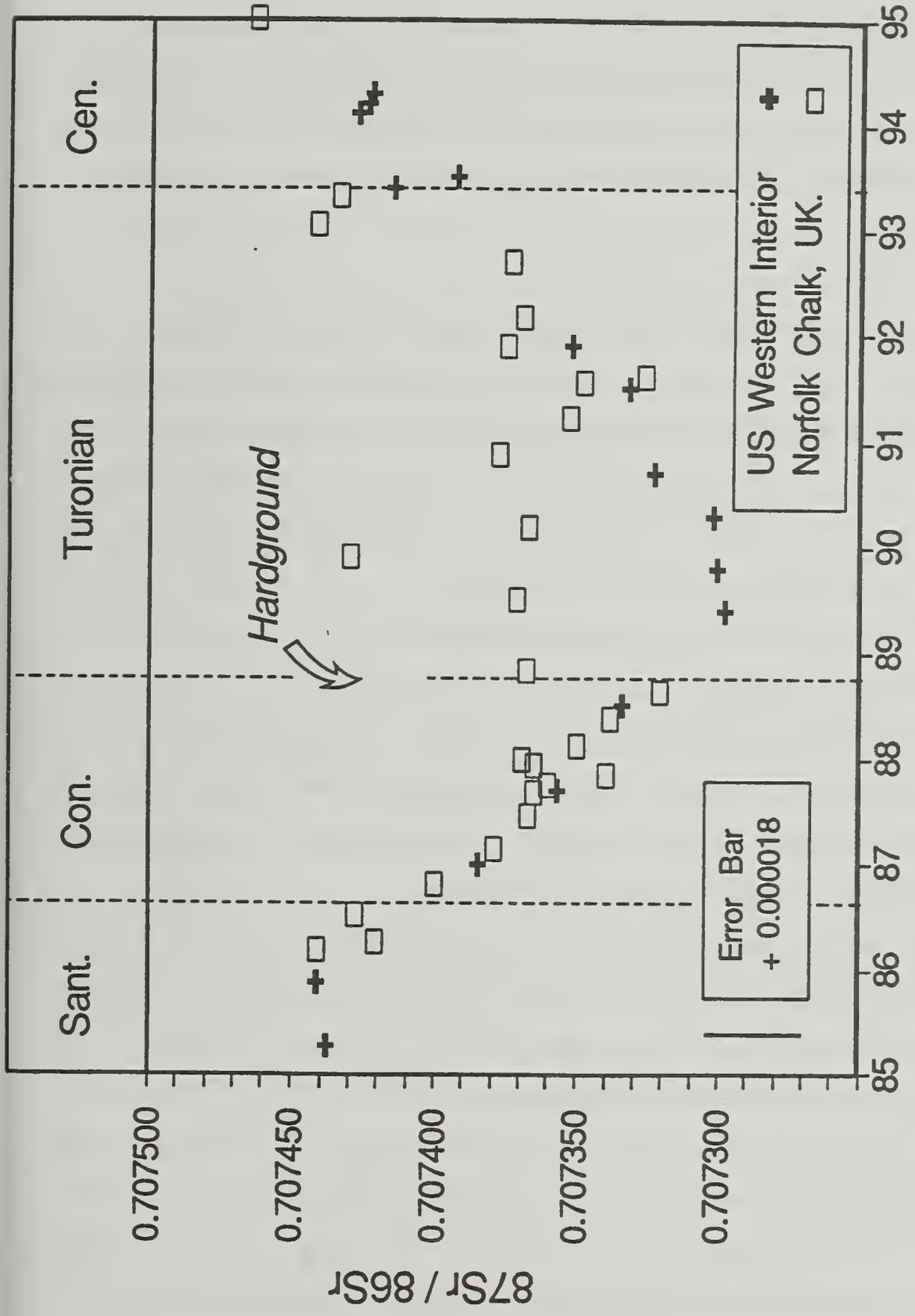

Fig.5. The effect of hardground formation on $^{87}Sr/^{86}Sr$ in the Chalk, shown by comparing the $^{87}Sr/^{86}Sr$ profile for Trunch and the U.S. western interior (McArthur et al., 1994a).

nothing more than obscure the finer coccolith structure. As macrofossils suitable for analysis are not common in the chalk cores, the trend in $^{87}Sr/^{86}Sr$ has been defined largely by the more abundant nannofossil data, although it is drawn through the macrofossil data.

The Sr content of the Chalk at Trunch was discussed by Bath and Edmunds (1981), so no further discussion is called for beyond noting that Sr concentrations in the Chalk are highest around 300m depth and do not correlate with lithology or $^{87}Sr/^{86}Sr$. There are no anomalous concentrations of Sr around 225m, where the Sr-isotope curve shows a pronounced inflexion.

Application of the $^{87}Sr/^{86}Sr$ Profile to Correlation and Dating

When using figures 3 and 4 for correlation and dating, analytical uncertainties are present both in the measurement of $^{87}Sr/^{86}Sr$ of the unknown and in the calibration curve. These uncertainties must be compounded in order to obtain a realistic assessment of the total uncertainty involved in correlating and dating strata with figures 3 and 4. The total uncertainty may be approximated using the formula $s_{total} = (s_1 + s_2)^{½}$, where s_1 and s_2 are the uncertainty of measurement at one standard deviation of the calibration line and the unknown respectively. For uncertainties of determination in $^{87}Sr/^{86}Sr$ of $\pm 9 \times 10^{-6}$, this gives an uncertainty in correlation of ± 13, for comparison of single determinations of $^{87}Sr/^{86}Sr$ with the standard curve (Fig. 3). With this uncertainty, and a rate of change of $^{87}Sr/^{86}Sr$ through the Coniacian/Early Maastrichtian of 23×10^{-6} myr^{-1}, the uncertainty in correlation and dating is about ± 0.5 myr or 14m of section.

Between the Campanian/Maastrichtian boundary (71.3 ± 1 Ma) and the Turonian/Coniacian boundary (88.7 ± 1 Ma), $^{87}Sr/^{86}Sr$ increased by 400×10^{-6} (Table 1), which was a rate of increase of between 21×10^{-6} and 26×10^{-6} myr^{-1}, the range deriving from the errors on the numerical dates. The mean rate was 23×10^{-6} myr^{-1}. If that rate of increase had persisted through all of Maastrichtian time, the $^{87}Sr/^{86}Sr$ at the Cretaceous/Tertiary boundary would have been 0.70786, if this boundary is assigned a numeric age of 65.4 ± 1 myr (Obradovich, 1994). The actual value is 0.70783 (Mc Laughlin et al., in press), so the rate must have declined slightly during Maastrichtian time.

SUMMARY

Isotopic analysis of the English Chalk and contained macrofossils shows that marine $^{87}Sr/^{86}Sr$ decreases from 0.70743 in the Cenomanian to 0.70730 in the middle Turonian before increasing in a near-linear manner to about 0.70775 in the early Early Maastrichtian. Hardground formation disturbs the $^{87}Sr/^{86}Sr$ values between 432m and 470m, and between 210m and 250m. During the Coniacian-Maastrichtian the rate of increase was between 21×10^{-6} and 26×10^{-6} myr^{-1}. Macrofossils yield $^{87}Sr/^{86}Sr$ that are about 30×10^{-6} lower than nannofossil data. The Norfolk Chalk and its macrofossils appear, for the most part, to be good preservers of Late Cretaceous marine $^{87}Sr/^{86}Sr$. The profile of $^{87}Sr/^{86}Sr$ provides a standard curve for correlation to the English Chalk from localities world-wide that is independent of magneto-stratigraphy or biostratigraphy. Correlation can be achieved with a temporal resolution that is typically ± 0.5 myr, and a stratigraphic resolution that is typically ± 14m of section, for the Santonian and Campanian stages, where the curve has its steepest slope and is best defined.

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REFERENCES

BATH, A.H. & EDMUNDS, W.M. 1981. Identification of connate water in interstitial solution of chalk sediment. *Geochimica et Cosmochimica Acta*, **45**, 1449-1461.

BIRKELUND, T., HANCOCK, J.M., HART, M.B., RAWSON, P.F., REMANE, J., ROBASZYNSKI, F., SCHMID, F. & SURLYKE, F. 1984. Cretaceous stage boundaries; proposals. *Bulletin of the Geolical Society of Denmark*, **33**, 3-20.

BROMLEY, R.G. 1979. Chalk and Bryozoan limestone facies, sediments and depositional environments. In: Birklund, T. & Bromley, R.G. (eds). *Cretaceous-Tertiary boundary events. 1. The maastrichtian and Danian of Denmark*, 16-35, Univ. Copenhagen.

BURNETT J.A. 1988. North-West European Late Cretaceous calcareous nannofossils: biostratigraphy and selected evolutionary lineages. Ph.D thesis, University College London, (unpub), 364pp.

BURNETT, J.A. 1990. A new nannofossil zonation scheme for the Boreal Campanian. *INA Newsletter*, **12/3**, 67-70.

FARRELL J.W., CLEMENS, S.C. and GROMET P.L. 1995. Improved chronostratigraphic reference curve of Late Neogene seawater $^{87}Sr/^{86}Sr$. *Geology*, in press.

GALLOIS, R.W. & MORTER, A.A. 1975. East Anglia and South-East England District. Mundesley (132) sheet. Trunch Borehole (TG 2933 3455). *Institute of Geological Sciences Report*, **76/10**, 8-10.

HANCOCK, J.M. 1975. The petrology of the Chalk. *Proceedings of the Geologists Association*, **86**, 499-535.

HESS, J., BENDER, M.L., & SCHILLING, J-G. 1986. Evolution of the ratio of strontium-87 to strontium-86 in seawater from Cretaceous to Present. *Science*, **231**, 979-984.

HESS J., STOTT L.D., BENDER M.L., KENNET J.P AND SCHILLING J-G. 1989. The Oligocene marine microfossil record: age assessments using strontium isotopes. *Paleoceanography*, **4**, 655-679.

HODELL, D.A. 1991. Variations in the strontium isotopic composition of seawater during the Neogene. *Geology*, **19**, 24-27.

HODELL, D.A. and WOODRUFF, F. 1994. Variations in the strontium isotopic ratio of seawater during the Miocene: Stratigraphic and geochemical implications. *Paleoceanography*, 9, 405-426.

HODELL, D.A., MUELLER, P.A., MCKENZIE, J.A. & MEAD, G.A. 1989. Strontium isotope stratigraphy and geochemistry of the late Neogene ocean. *Earth and Planetary Science Letters*, **92**, 165-178.

HODELL D.A., MEAD G.A. AND MUELLER P.A. 1990. Variation in the strontium isotopic composition of seawater (8 Ma to present): implications for chemical weathering rates and dissolved fluxes to the oceans. *Chemical Geology. (Isotope Geosciences Section)*, **80**, 291-307.

JONES C.E., JENKYNS H.C. and HESSELBLO S.P. 1994a. Strontium isotopes in Early Jurassic seawater. *Geochimica et Cosmochimica Acta*, 58, 1285-1301.

JONES C.E., JENKYNS H.C., COE A.L. and HESSELBLO S.P. 1994b. Strontium isotopic variations in Jurassic and Cretaceous seawater. *Geochimica et Cosmochimica Acta*, 58, 3061-3074.

McARTHUR J.M., THIRLWALL M.F., GALE A.S., KENNEDY W.J., BURNETT J.A., MATTEY D. AND LORD A.R. 1993a. Strontium-isotope stratigraphy for the Late Cretaceous: a new curve, based on the English Chalk. In E. Hailwood and R. Kid (eds.), *High Resolution Stratigraphy. Geological Society of London, Special Publication*, **70**, 195-209.

McARTHUR J.M., CHEN M., GALE A.S., THIRLWALL M.F. AND KENNEDY W.J. 1993b. Strontium-isotope stratigraphy for the Late Cretaceous: age models and intercontinental correlations for the Campanian. *Paleoceanography*, **8**, 859-873.

McARTHUR J.M., KENNEDY W.J., CHEN M., THIRLWALL M.F. AND GALE A.S. 1994a. Strontium isotope stratigraphy for the Late Cretaceous: direct numerical age calibration of the Sr-isotope curve for the U.S. Western Interior Seaway. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 108, 95-109.

McARTHUR J.M. 1994b. Recent trends in strontium isotope stratigraphy. *Terra Nova*, 6, 331-358.

M^{C} LAUGHLIN Ó.M., McARTHUR J.M., THIRLWALL M.F., ZINSMEISTER W.J., GALE A.S. & KENNEDY W.J. Marine evolution of $^{87}Sr/^{86}Sr$ across the K/T boundary. Submitted to *Earth and Planetary Science Letters*.

MILLER, K.G., FEIGENSON, M.D., KENT, D.V. & OLSON, R.K. 1988. Upper Eocene to Oligocene isotope ($^{87}Sr/^{86}Sr$, d18O, d13C) standard section, Deep Sea Drilling Project Site 522. *Paleoceanography*, **3**, 223-233.

MILLER K.G., FEIGENSON M.D., WRIGHT J.D. AND CLEMENT B.M. 1991. Miocene isotope reference section, Deep Sea Drilling Project Site 608: an evaluation of isotope and biostratigraphic resolution. *Paleoceanography*, **6**, 33-52.

MORTER A.A. and R.W. GALLOIS 1979. Provisional report on the IGS borehole drilled at Trunch, Norfolk. *Unpublished Report of the Intitute of Geological Sciences.*

MORTIMORE, R.N. 1986. Stratigraphy of the Upper Cretaceous White Chalk of Sussex. *Proceedings of the Geologists Association*, **97**, 97-139.

OBRADOVICH J.D. A Cretaceous time scale 1993 *In* W.G.E. Caldwell and E. Kauffman (eds.). *Evolution of the Western Interior Foreland Basin*, Geological Association of Canada, Special Paper 39, 379-396.

OSLICK J.S., MILLER K.G. AND FEIGENSON M.D. 1994 Oligocene-Miocene strontium isotopes: stratigraphic revisions and correlations to an inferred glacioeustatic record. *Paleoceanography*, 9, 427-443.

PAYTAN A., KASTNER M., MARTIN E.E., MACDOUGALL J.D. AND HERBERT T. 1993. Marine Barite as a monitor of seawater strontium isotope composition. *Nature*, *366*, 445-449.

PEAKE, N.B. & HANCOCK J.M. 1961. The Upper Cretaceous of Norfolk. *Transactions of the Norfolk and Norwich Nature Society*, **19**, 293-339.

PERCH-NIELSEN, K. 1979. Calcareous nannofossils from the Cretaceous between the North Sea and the Mediterranean. *I.U.G.S. Series A*, **6**, 223-272.

PERCH-NIELSEN, K. 1985. Mesozoic calcareous nannofossils. In: Bolli, H.M., Saunders, J.B. & Perch-Nielsen, K., (eds) *Plankton stratigraphy*.

RAWSON, P.F., CURRY D., DILLEY F.C., HANCOCK J.M., KENNEDY W.J., NEALE J.W., WOOD C.J. & WORSSAM B.C. 1978. A correlation of Cretaceous rock in the British Isles. *Geological Society of London Special Report*, **9**, 80pp.

SUGARMAN, P.J., MILLER, K.G., BUKRY, D and FEIGENSON, M.D., 1995. Uppermost Campanian-Maestrichtian strontium isotopic, biostratigraphic, and sequence stratigraphic framework of the New Jersey Coastal Plain. *Bulletin of the Geological Society of America*, 107, 19-37.

SISSINGH, W. 1977. Biostratigraphy of Cretaceous Nannoplankton. *Geologie en Mijnbouw*, **56**, 37-65.

THIRLWALL M.F. 1991. Long term reproducibility of multi-collector Sr and Nd isotope ratio analysis. *Chemical Geology*, *94*, 85-104.

WICKMAN F.E. 1948. Isotope ratios: a clue to the age of certain marine sediments. *Journal of Geology*, **56**, 61-66.

WOOD, C.J. MORTER, A.A. and GALLOIS, R.W. 1994. Upper Cretaceous stratigraphy of the Trunch Borehole (TG 23 SE 8). *In*: Arthurton, R.S., Booth, S.J., Morigi, A.N., Abbott, M.A.W. & WOOD C.J., *Geology of the Country around Great Yarmouth*. Memoir for 1:50 000 geological sheet 162 (England and Wales). HMSO, London.

GLOSSARY

Isotope: Atoms consist of a nucleus containing protons and neutrons surrounded by a cloud of electrons. All atoms of an element, such as strontium, have the same number of protons in the nucleus but they may have differing numbers of neutons; these differing atoms are termed isotopes of the element. For example, all Sr atoms contain 38 protons, but may have 46, 48, 49 or 50 neutrons. The numerical sum of the protons and neutrons is called the mass number, and is commonly written as a left-handed superscript to the element symbol; the isotopes of Sr are therefore written as ^{84}Sr, ^{86}Sr, ^{87}Sr, and ^{88}Sr.

A RE-EXAMINATION OF LACUSTRINE CARBONATE FORMATION IN HOLKHAM LAKE, NORTH NORFOLK

David Lucas

School of Environmental Sciences,
University of East Anglia,
Norwich NR4 7TJ

ABSTRACT

Holkham Lake in north Norfolk has become world renowned as the only known site where vaterite (an extremely unusual polymorph of calcium carbonate) forms in natural waters. Detailed re-examination of the lakes carbonate chemistry and mineralogy during 1993-1994 failed to identify vaterite formation. It is unclear why vaterite is not present and it is possible that the original identification was wrong. Today, as in many other lakes, calcite precipitates in the water column of Holkham Lake. The conditions under which calcite forms are constrained by chemical and stable isotopic data which suggest that calcite precipitation is associated with photosynthetic activity in the spring and early summer as the lake water warms. Isotopic mass balance shows that most of the lake bed calcite sediment is accumulated water column precipitate.

INTRODUCTION

Holkham Lake, situated in the grounds of Holkham Hall, near Wells-next-the-Sea, north Norfolk (GR TF 883430) is an artificial lake created in the mid-eighteenth century. The lake water has been known to develop an opalescent appearance during late spring because of calcium carbonate precipitation (Rowlands and Webster, 1971). It is not unusual for fine-grained carbonates to precipitate in the water column of lakes and these are often referred to as "whitings". These precipitates are usually the mineral calcite ($CaCO_3$), although aragonite, Mg-calcite and dolomite are also known (Muller *et al.*,

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1972; Talbot, 1990). Holkham Lake, however, is reported to be unique because it precipitates vaterite, a microcrystalline form of calcium carbonate that is exceptionally rare in nature (Rowlands and Webster, 1971). There is no other published example of natural lacustrine vaterite precipitation anywhere else in the world.

The original aim of this study was twofold. Firstly to ascertain why vaterite might precipitate only in Holkham Lake and secondly, to understand more about the isotope geochemistry of naturally forming vaterite.

Study Area

Holkham Lake is a shallow (1-1.5 m deep), artificial lake about 1 km long and 40 m wide, which is recharged by springs at the south end, the most obvious of which is 10 m to the north of the weir, on the east bank (Fig. 1). Other springs discharge subaqueously in the region of site U_2 (Fig. 1) but were not located exactly. The outlet of the lake is at the northern-most point where a sluice allows discharge to marshes and ultimately the North Sea.

The weir (Fig. 1) separates the lake into upper (U) and lower (L) parts, the southern and northern ends respectively. The water level in the upper lake is less than half a metre above the lower lake level. The rate of water flow over the weir is very low being virtually zero on three of five visits, even in July, when there was heavy rainfall for the three days preceding sampling. Therefore it appears that the springs in the upper lake have a low discharge.

The lake water is generally quite clear, although the upper lake and the northern end of the lower lake contains benthic algae and decaying organic matter. The distribution of detrital organic matter may simply have resulted from dredging of the southern part of the lower lake in the early 1990s, clearing it of plant material. However, at the northern end and beside the upper lake (north bank) there are overhanging trees and shrubs which may deposit organic matter directly into the water.

The carbonate mineralogy of the lake has not been studied since Rowlands and Webster (1971) reported the occurrence of vaterite. The following section gives a brief outline of vaterite and its reported occurrence.

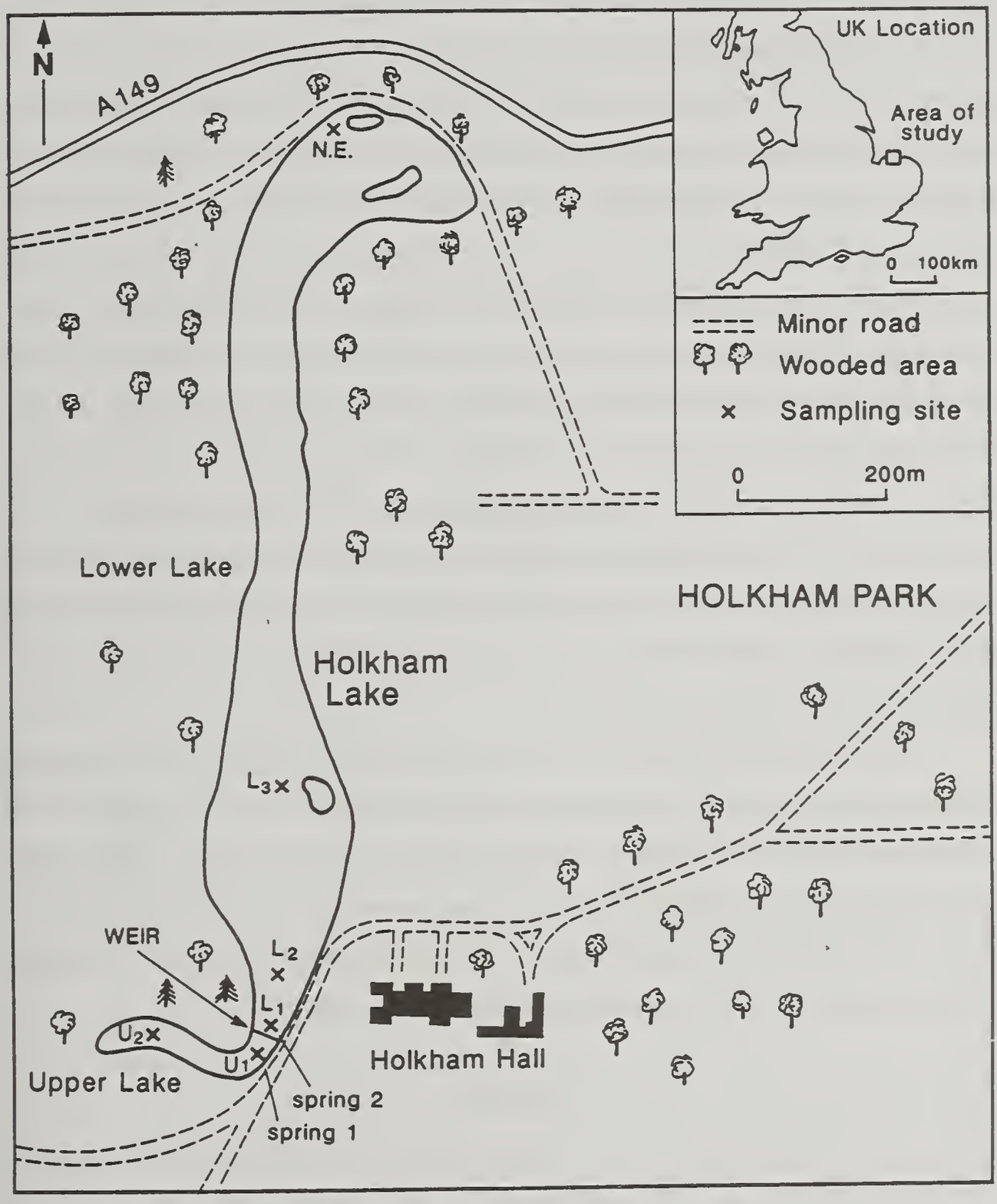

Fig. 1. Location map of the study area.

Vaterite

Vaterite, the third polymorph of $CaCO_3$ (after calcite and aragonite) was named in 1911 following laboratory synthesis (Meigen, 1911) and was later reported to occur in nature (Mayer and Weinbeck, 1932). Vaterite has a relatively low density of 2.65 g cm^{-3}, is platy, has a high birefringence and is metastable with respect to calcite and aragonite under certain geological circumstances (Carlson, 1983). Although often regarded as little more than a laboratory curiosity (Tucker and Wright, 1990), it has been noted that it occurs naturally in the repair tissue of certain gastropods (Carlson, 1983), in human gallstones (Sutor and Wooley, 1967) and in rocks (Bentnor, 1963; McConnell, 1960). McConnell (1960) suggests that vaterite is rare because it is unstable at room temperature and pressure and readily transforms to calcite when heated (dry) to 400°C. Northwood and Lewis (1968) showed that vaterite changes to calcite when subjected to shear strains which might explain why it is rare in the Earth's crust. Lippmann (1973) states that vaterite is not found in natural carbonate sediments and would only be expected to form under specialised conditions and even then only as a transitory phase. These specialised conditions may include high alkalinity (Scoffin, 1987) or the presence of pollutants and surfactants (Nathan, 1971).

There is some debate as to the stability of vaterite. From the preceding discussion, vaterite would be expected to transform to calcite under usual Earth surface conditions. However, Friedman *et al.* (1993) have shown that vaterite, formed within rotary cuttings while boring through Ordovician carbonates, has persisted for eleven years. This supports the earlier comments of Albright (1971) who says that vaterite may be relatively stable even when calcite is the predicted stable mineral.

METHODS

Holkham Lake was sampled on five occasions during 1993-1994 (June 1993, July 1993, November 1993, February 1994, and June 1994) at the sample sites shown in Figure 1. Sampling was done over a period of one year to study seasonal changes in water chemistry. The degree of saturation (Ω) of the lake water with respect to the common carbonate minerals calcite, aragonite and dolomite was calculated using the computer program WATEQP (Appelo, 1988). In order to do this, the calcium (Ca^{2+}) and magnesium (Mg^{2+}) ion concentrations, alkalinity, pH and temperature of the lake were measured. From a small boat, temperature and pH were measured directly using a

mercury thermometer and pH meter respectively, just below the lake surface. Two 250 ml water samples were collected in plastic bottles at each site, one of which was filtered through a glass microfibre filter so that Ca^{2+} and Mg^{2+} concentrations could be measured in the laboratory using an atomic absorption spectrophotometer. The other water sample was analyzed for alkalinity by EDTA titration. For a given mineral, if log Ω is <0 then the water is undersaturated, and if log Ω is >0 then the water is supersaturated with respect to that mineral. Ω is affected by Ca^{2+} concentration, alkalinity, pH and concentration (partial pressure) of carbon dioxide; the results of these are examined below. Ω values thus indicate whether water might be expected to precipitate, dissolve or be in equilibrium with minerals. However, natural water often needs to be very supersaturated before precipitation of a mineral occurs (Kelts and Hsü, 1978; Michaelis *et al.*, 1985).

Since Müller *et al.* (1972) showed that the Mg/Ca ratio of lake water can affect the species of carbonate precipitated, the magnesium concentration of the water was measured to investigate its effect on the occurrence of vaterite. Five litre water samples were collected in July, November and June (1994) from each site to identify carbonate minerals that may have precipitated in the water column. These samples were filtered through GFC filters and the solids identified by x-ray diffraction (XRD) (see below).

Chlorophyll *a* was measured (method of Parsons *et al.* 1984) as an indicator of primary production in the water column, since Rowlands and Webster (1971), when reporting vaterite precipitation in Holkham Lake, considered biological activity to be a factor in its formation. Mengard (1968) found that the rate of carbon fixation by plants was related linearly to a decrease in Ca^{2+} concentration and alkalinity (presumably due to $CaCO_3$ precipitation). It is known that the degassing of CO_2 either by wind action or by biological uptake can affect the pH of the water body which in turn can cause $CaCO_3$ precipitation (Pentecost, 1981). The partial pressure of CO_2 in the water column was calculated using the computer program WATEQP.

Phosphate concentration was measured by the method of Murphy and Riley (1962) because it can affect $CaCO_3$ precipitation and dissolution in different ways. It may encourage vaterite precipitation (Nathan, 1971), inhibit the dissolution of $CaCO_3$ even when the solution is supersaturated with respect to that mineral (Kelts and Hsü,

1978) and at high concentration can inhibit the crystallisation of calcite even in a highly saturated solution (Kleiner, 1988).

Surface lake bed sediment samples and material suspended in the water column were analyzed by XRD to identify the minerals present. Sediment samples were ground, made into a paste and spread onto a glass slide for analysis on a Phillips PW 1710 X-ray diffractometer. The suspended solids samples were cut out from the filter papers on which they were deposited and stuck onto an XRD slide for analysis.

Isotope geochemistry

Water column precipitation of vaterite has only ever been reported in Holkham Lake and the isotope geochemistry of such natural vaterite precipitation has never been studied. By analysing the carbon and oxygen isotopic composition of water, dissolved inorganic carbonate (DIC) in the water column and carbonate sediment on the lake bed, it should be possible to establish the isotopic equilibrium relationship for carbon and oxygen in the precipitating $CaCO_3$.

The theoretical oxygen isotope composition ($\delta^{18}O$) of carbonate is determined by the isotopic composition of the ambient water and water temperature assuming equilibrium conditions. Enrichment of ^{18}O in lake waters relative to the inputting spring waters could indicate evaporation of lake waters, since evaporation preferentially removes the more reactive ^{16}O isotope in the vapour (Faure, 1977). leaving the water enriched in ^{18}O.

Carbon isotope compositions ($\delta^{13}C$) reflect the source of carbon. Within the water column the $\delta^{13}C$ of dissolved HCO_3^- (DIC) is determined by the relative contributions of different sources of carbon (see Table 1). For example $HCO_{3\,(aq)}^-$ derived predominantly from organic carbon would have a $\delta^{13}C$ value of approximately -15‰ (Arthur *et al.*, 1983). In a recent discussion of $\delta^{13}C$ in dissolved HCO_3^- derived from the decay of organic matter, Andrews *et al.* (1993) suggested that values smaller than -16.5‰ are unlikely. The $\delta^{13}C$ of dissolved HCO_3^- can also be modified by equilibrium of HCO_3^- with atmospheric CO_2, and by the preferential withdrawal of the light ^{12}C atoms during photosynthesis (Pearson and Caplen, 1978). Andrews *et al.* (1993) suggested that photosynthesis is not usually the cause of significant carbon

Table 1: $\delta^{13}C_{PDB}$ values by source, ‰ (Arthur *et al.*, 1983)

Source	$\delta^{13}C$ ‰
lacustrine plants	-26
CO_2 from organic decay	-24
algal organic matter	-16
atmospheric CO_2	-7 to -6
carbonate rocks	-3 to +3

isotope fractionation in most British lakes and that equilibrium with atmospheric CO_2 is more important.

Surface sediment samples for isotope analysis were collected from all sites during June 1993 and from three sites during June 1994. For isotope analysis, sediments had volatile organic matter removed by low temperature (<80°C) plasma ashing. About 5 mg of carbonate sample was reacted with 102% phosphoric acid under vacuum to produce CO_2. This was cleaned by cryodistillation through a cold trap at -70°C and then collected for mass spectrometric analysis on a VG SIRA II mass spectrometer. All results are Craig corrected and are reported in delta notation (δ) as parts per thousand (‰ or per mil) relative to the VPDB international scale, i.e.

$$\delta = \left(\frac{R_{sample} - R_{standard}}{R_{standard}} \right) \times 1000$$

Where R represents a stable isotope ratio and δ expresses the difference between the isotopic ratios of the sample and the standard. δ is positive when the sample has a larger ratio than the standard, is negative when the reverse is true and is zero when both values are the same.

Isotope analysis of dissolved inorganic carbon (DIC) was made using the method of Bishop (1990) and the evolved CO_2 was analyzed as above.

Water samples were collected in glass McCartney bottles for oxygen isotope analysis. Sample preparation involved equilibrating a small amount of the water with CO_2 gas as described by Epstein and Mayeda (1953). The equilibrated CO_2 gas was

purified of any remaining water vapour and transferred to a gas tube ready for analysis on the mass spectrometer. All the results were Craig corrected and the δ values are reported relative to the VSMOW international scale.

RESULTS

Saturation state of the water column

Results from this study are tabulated in Tables 2 and 3. Table 2 shows saturation indices (Ω) of the lake water with respect to calcite, aragonite and dolomite and these are shown graphically in Figure 2. The lake is most supersaturated with respect to calcite in July in the lower lake. The only other time it is supersaturated is at L_3 in November and at the north end in June 1994. Throughout the year the spring water was undersaturated with respect to calcite and (as can be seen clearly in Figure 2) Ω increases immediately downstream of the spring.

In the upper lake the water is moving towards the weir and tends towards equilibrium except in February where perhaps the discharge of spring 1 is influencing the composition of water at U_1. Table 2 shows that only in July at sites L_1, L_2 and L_3 was the water supersaturated with respect to aragonite and dolomite.

Mineralogy

The most common mineral found in the lake bed sediment is calcite although quartz was also present at all sites analyzed in June 1993. No vaterite, aragonite or dolomite was detected.

The only mineral found suspended in the water column was calcite; no vaterite, aragonite or dolomite was identified. At some sites (for example L_1 and L_2 in July) there were no minerals in the water column, although it is possible that calcite was present but at very low concentration. It is also possible that other minerals (such as vaterite) were also present at very low concentrations. This possibility was tested with sample L_1 (June 1994) which was XRD analyzed first on the filter and then again having been washed from the filter. The second run tested the noise contributed from the filter paper. There was little difference between the two methods and no previously hidden minerals were revealed.

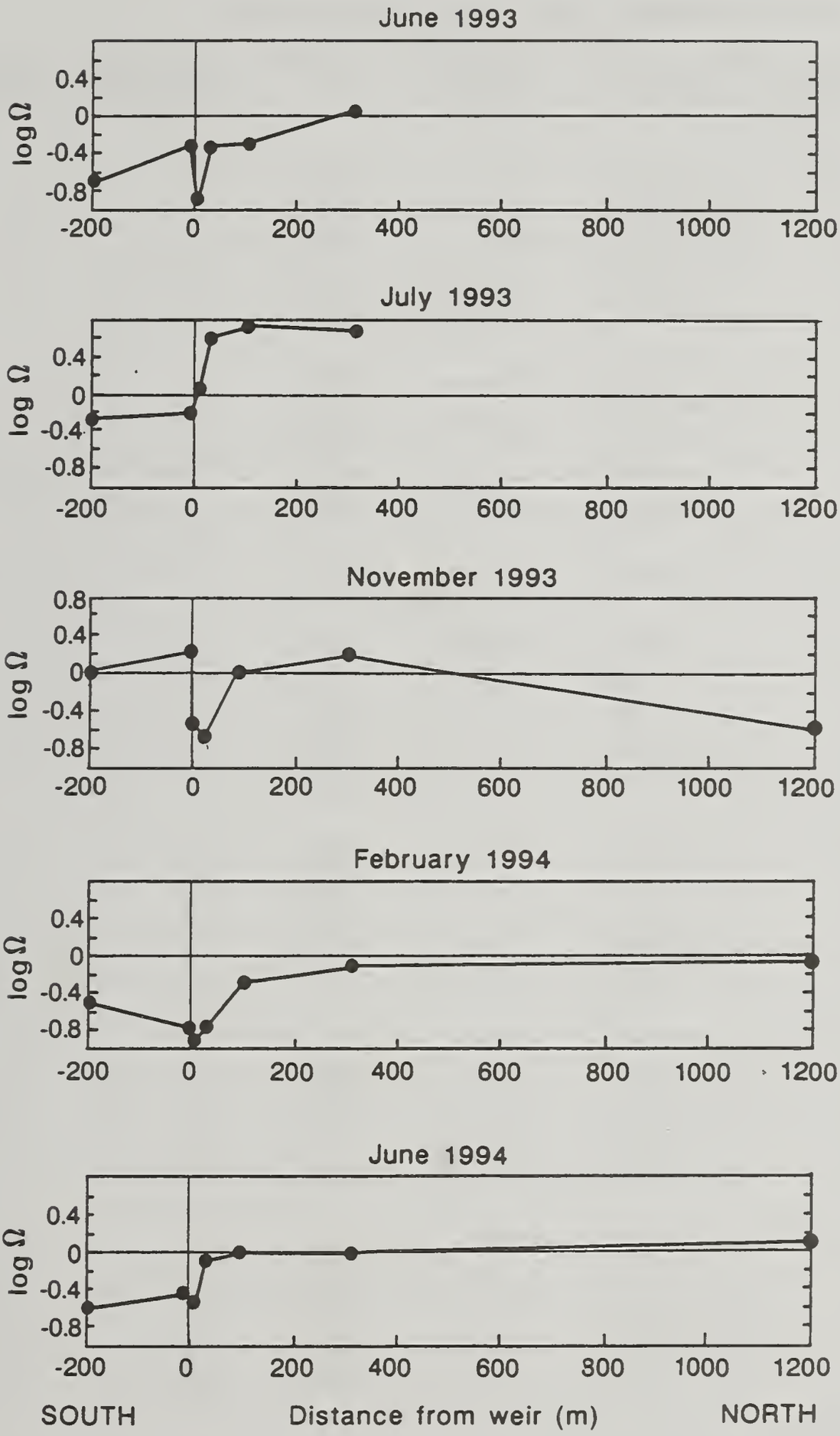

Fig. 2. Plot of log calcite saturation index (Ω) versus distance from the weir for various sample dates, Holkham Lake.

Table 2. Data from Holkham Lake - June 1993 to June 1994

Site	Metres from weir	Date	Temp. (°C)	pH	Chlorophyll *a* (±2 μgl^{-1})	Alkalinity (±0.1 $meql^{-1}$)
U_2	-200	18.6.93	18.5	7.43	0.3	0.5
		27.7.93	16.7	7.89	3.0	1.5
		4.11.93	10.0	7.30	11.2	4.2
		24.2.94	4.1	7.55	8.0	0.7
		14.6.94	20.0	8.80	2.3	0.18
U_1	-5	18.6.93	19.5	7.67	0.0	0.6
		27.7.93	17.0	7.98	7.0	1.3
		4.11.93	10.0	7.45	---	4.1
		24.2.94	4.8	7.46	8.91	0.65
		14.6.94	19.0	7.80	2.31	0.3
Spr. 1	-3	24.2.94	8.8	7.13	0.0	0.55
Spr. 2	10	18.6.93	10.0	7.10	0.0	0.6
		27.7.93	12.0	7.38	0.7	4.5
		4.11.94	11.5	6.64	0.0	4.9
		24.2.94	9.1	7.13	0.0	0.55
		14.6.94	11.0	7.52	3.6	0.18
L_1	30	18.6.93	18.0	7.66	1.6	0.6
		27.7.93	16.2	8.74	3.3	1.3
		4.11.94	10.0	6.65	3.1	4.3
		24.2.94	5.6	7.36	6.8	0.5
		14.6.94	19.0	7.97	3.1	0.42
L_2	100	18.6.93	19.0	7.71	2.2	0.6
		27.7.93	16.9	8.82	5.3	1.5
		4.11.93	9.5	7.44	4.4	3.7
		24.2.94	2.0	7.90	8.3	0.6
		14.6.94	19.0	8.08	0.0	0.4
L_3	310	18.6.93	19.0	8.18	2.2	0.5
		27.7.93	17.0	8.88	3.3	1.4
		4.11.93	9.5	7.62	---	3.7
		24.2.94	2.4	8.08	12.7	0.6
		14.6.94	19.0	8.08	0.0	0.43
North End	1200	18.6.93	---	---	---	---
		27.7.93	---	9.81	---	---
		4.11.93	9.5	7.06	9.5	3.1
		24.2.94	3.2	8.20	9.4	0.4
		14.6.94	20.0	8.65	3.0	0.24

Phosphate ($\pm 1.0\ \mu g l^{-1}$)	Mg ($\pm 0.1\ mg l^{-1}$)	Ca	Mg/Ca	pCO_2 (atms)	log Ω calcite	log Ω aragonite	log Ω dolomite
---	3.2	81.0	0.039	$10^{-2.99}$	-0.68	-0.83	-2.54
0.0	3.1	28.3	0.110	$10^{-2.98}$	-0.19	-0.35	-1.14
22.0	3.0	93.5	0.032	$10^{-1.99}$	0.00	-0.15	-1.35
---	2.3	122.1	0.019	$10^{-3.05}$	-0.49	-0.65	-2.64
---	4.3	74.0	0.058	$10^{-2.99}$	-0.60	-0.76	-2.65
---	3.3	83.9	0.039	$10^{-3.15}$	-0.34	-0.49	-1.85
0.3	3.0	26.5	0.113	$10^{-3.13}$	-0.19	-0.34	-1.11
107.0	3.2	93.4	0.034	$10^{-2.15}$	0.14	-0.01	-1.04
---	3.6	123.5	0.029	$10^{-2.99}$	-0.60	-0.76	-2.65
---	4.0	94.0	0.043	$10^{-3.59}$	-0.48	-0.62	-2.10
---	5.9	123.9	0.048	$10^{-2.55}$	-0.78	-0.93	-2.75
---	2.6	124.8	0.021	$10^{-2.64}$	-0.89	-1.05	-3.34
19.0	3.0	72.4	0.041	$10^{-2.03}$	0.05	-0.11	-1.13
15.0	2.7	92.6	0.029	$10^{-1.26}$	-0.57	-0.73	-2.53
---	5.0	124.1	0.040	$10^{-2.71}$	-0.93	-1.09	-3.13
---	4.0	134.0	0.030	$10^{-3.14}$	-0.53	-0.68	-2.43
---	3.3	90.0	0.037	$10^{-3.15}$	-0.34	-0.49	-1.90
56.0	2.9	32.7	0.089	$10^{-3.93}$	0.60	0.45	0.36
30.0	3.3	88.3	0.037	$10^{-1.33}$	-0.66	-0.81	-2.60
---	4.1	118.7	0.035	$10^{-2.96}$	-0.77	-0.93	-2.83
---	3.8	106.0	0.036	$10^{-3.62}$	-0.12	-0.27	-1.46
---	3.2	85.0	0.038	$10^{-3.20}$	-0.30	-0.45	-1.79
11.2	2.8	31.1	0.090	$10^{-3.95}$	0.74	0.59	0.63
120.0	2.8	75.1	0.037	$10^{-2.18}$	0.00	-0.15	-1.29
---	3.2	110.6	0.029	$10^{-3.48}$	-0.28	-0.45	-1.94
---	3.9	104.0	0.038	$10^{-3.75}$	-0.03	-0.18	-1.27
---	3.2	81.7	0.039	$10^{-3.76}$	0.06	-0.09	-1.05
17.0	2.8	35.8	0.078	$10^{-4.08}$	0.71	0.55	0.44
197.0	3.0	75.7	0.040	$10^{-2.37}$	0.18	0.03	-0.90
---	4.0	106.3	0.038	$10^{-3.66}$	-0.12	-0.28	-1.59
---	4.0	100.0	0.040	$10^{-3.73}$	-0.03	-0.18	-1.23
---	---	---	---	---	---	---	---
125.0	3.0	22.7	0.132	---	---	---	---
398.0	2.8	60.9	0.046	$10^{-1.88}$	-0.53	-0.68	-2.26
---	2.4	91.2	0.026	$10^{-3.77}$	-0.04	-0.20	-1.58
---	6.2	64.0	0.097	$10^{-4.56}$	0.12	-0.03	-0.55

Table 2 cont: Data from Holkham Lake - June 1993 to June 1994

Site	Date	Minerals Present		Field observations and comments
		sediment	water column	
U_2	18.6.93	calcite, quartz[1]	---[2]	The upper lake is quite
	27.7.93	---	calcite	plant-rich compared with
	4.11.93	---	calcite	lower lake. Only in Feb.
	24.2. 94	---	---	was there flow over weir
	14.6.94	---	---	from upper to lower lake.
U_1	18.6.93	calcite, quartz	---	For much of year upper lake
	27.7.93	---	calcite	was turbid; however in June
	4.11.93	---	nothing[3]	94 the water was clear
	24.2. & 14.6. 94	---	---	with much plant growth.
Spr.	18.6.93	calcite, quartz	---	Strongest spring flow in
2	27.7.93	---	---	November and February;
	4.11.93	---	---	only in February was the
	24.2.94	calcite	---	other spring (spring 1)
	14.6.94	---	---	flowing.
L_1	18.6.93	calcite, quartz	---	Most of year lower lake was
	27.7.93	---	nothing	clearer than upper lake;
	4.11.93	---	nothing	however, in June 94 the
	24.2.94	---	---	lower lake was noticeably
	14.6.94	---	calcite	more cloudy.
L_2	18.6.93	calcite, quartz	---	In July the lower Lake had
	27.7.93	---	nothing	greatest organic matter in
	4.11.93	---	nothing	the water column, yet was
	24.2.94	---	---	clear again in November.
	14.6.94	---	calcite	
L_3	18.6.93	calcite, quartz	---	
	27.7.93	---	calcite	
	4.11.93	---	nothing	
	24.2.94	---	---	
	14.6.94	---	calcite	
N.E.	18.6.93	quartz	---	The north end is relatively
	27.7.93	---	calcite	plant-rich compared with
	4.11.93	---	calcite	the rest of lower lake.
	24.2. & 14.6.94	---	---	

[1] Calcite was of higher XRD intensity then quartz when found together.
[2] indicates no data available
[3] i.e. no minerals identified by XRD

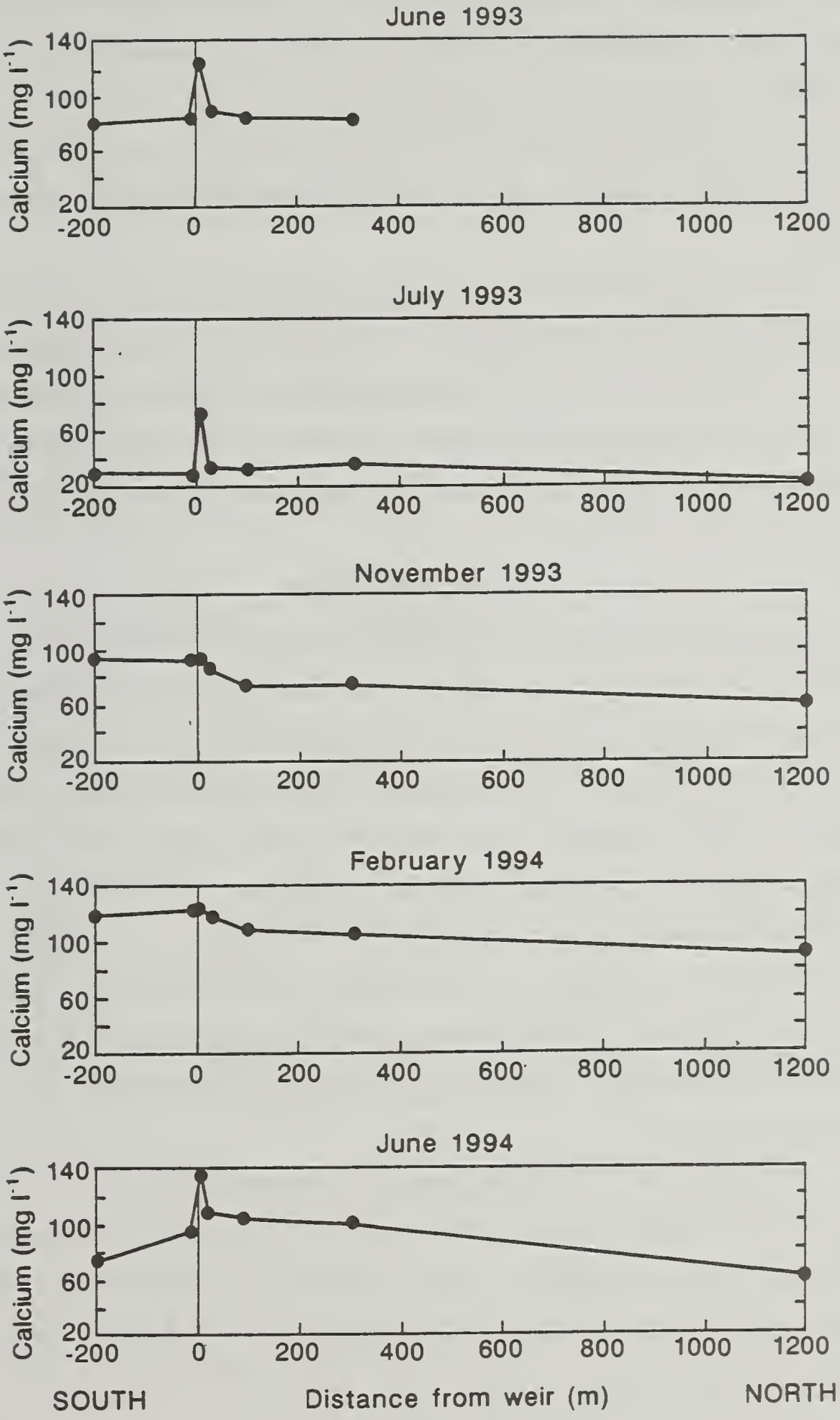

Fig. 3. Plot of calcium concentration versus distance from the weir for various sample dates, Holkham Lake.

Vaterite is described as metastable with respect to calcite, aragonite and dolomite (Calson, 1983). Since it is known to transform readily to calcite there is the possibility that vaterite was present in the water column but transformed to calcite before analysis. In order to test this, sample L_1 (June 1994) was filtered on site and analyzed by XRD within five hours of sampling. Even with such immediate analysis no vaterite was identified.

By comparing the data in Table 2 with that in Figure 2 it can be seen that only at L_3 during July was calcite present in the water column when the lake was supersaturated with respect to calcite. At all other times when calcite was present in the water column the lake was undersaturated with respect to calcite. This suggests that a simple relationship between supersaturated lake waters and calcite precipitation in the water column is not present.

Calcium and Alkalinity

The saturation index (Ω) for $CaCO_3$ is calculated by dividing the product of the activities of Ca^{2+} and CO_3^{2-} in the sample by the solubility product of the $CaCO_3$ mineral in question. With a higher concentration of Ca^{2+} and CO_3^{2-} the Ω value is higher.

Figure 3 shows that Ca^{2+} concentrations are always high in the spring and fall towards the north. Calcium ion concentration is highest in the lake in February (between 90 mg l^{-1} and 110 mg l^{-1}) and is lowest in July at around 20 mg l^{-1}. In the upper lake Ca^{2+} concentration increases slightly from U_2 to U_1.

Alkalinity is a measure of the total amount of weak acid anions in a solution which can react with H^+. In most natural waters the dominant anions (greater than 99%) are bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}). As pHs increase beyond 9, CO_3^{2-} becomes more important.

Alkalinity in June 1993, February and June 1994 is low and constant even at the spring (Fig. 4). However, in July 1993 the spring shows a markedly high alkalinity which falls off rapidly downlake to about 1.5 meq l^{-1}. Alkalinity in November is consistently high at around 3.5 meq l^{-1} although this does decrease slightly towards the north end.

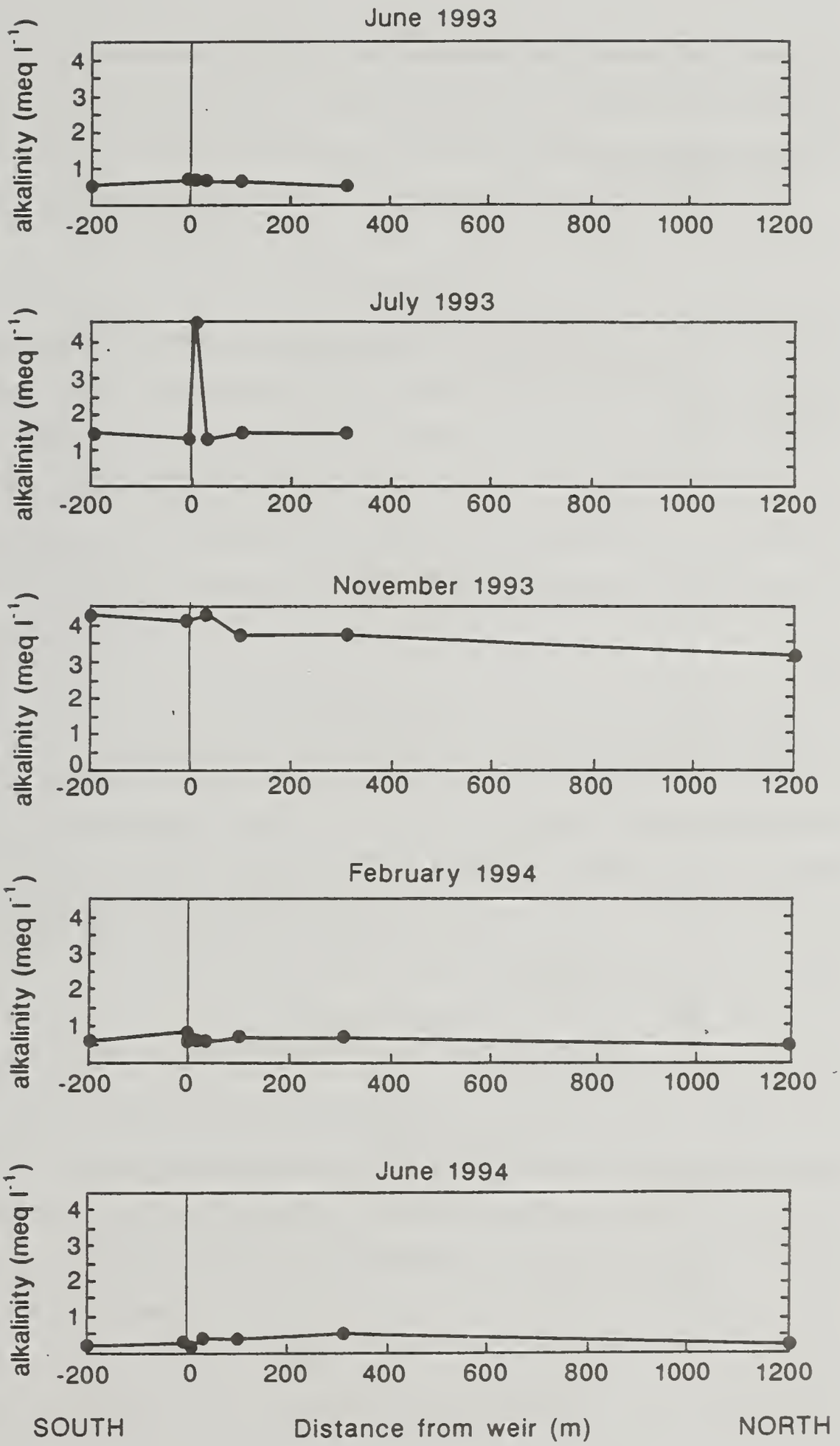

Fig. 4. Plot of alkalinity versus distance from the weir for various sample dates, Holkham Lake.

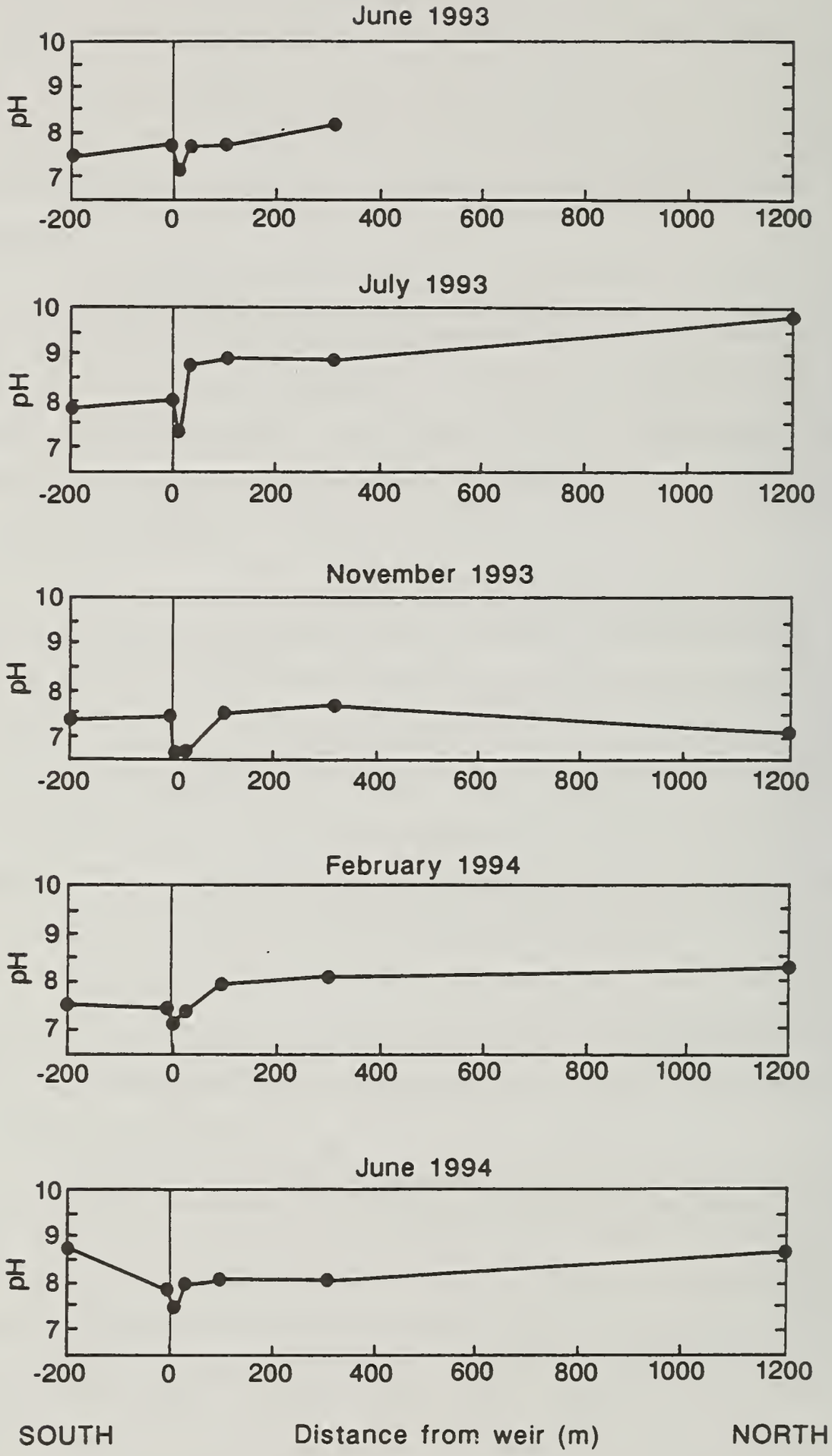

Fig. 5. Plot of pH versus distance from the weir for various sample dates, Holkham Lake.

pH

Figure 5 shows that at all times there is a sharp increase in pH immediately downlake of the spring. In June and July this rise continues at a slow rate reaching a maximum pH of 9.8 at the north end in July. In November and February the increase of pH downlake is not as rapid, in fact in November it falls to 7.1 at the north end of the lake.

Carbon Dioxide

The partial pressure of carbon dioxide (pCO_2) is shown in Figure 6. pCO_2 is high in the groundwater as it discharges from the spring and it falls quickly as the water moves north. However, the springwater pCO_2 is different through the year. It is high in November at about $10^{-2.2}$ atmospheres yet at other times of the year it is lower at around 10^{-4} atmospheres. As a comparison the pCO_2 of the atmosphere is $10^{-3.6}$ atmospheres. In the lower lake pCO_2 falls from U_2 to U_1 (except in February - perhaps due to the influence of spring 1).

Chlorophyll *a*

Rowlands and Webster (1971) considered photosynthesis to be a major influencing factor in the precipitation of vaterite. Chlorophyll *a* was used as an indicator of primary production by phytoplanktonic algae, but as Figure 7 shows, there is little relationship between chlorophyll *a* and $\Omega_{calcite}$ (correlation $r^2=0.04$).

Stable Isotopes

$\delta^{13}C$ DIC

Table 3 shows that dissolved inorganic carbon (DIC) in spring water has smaller isotopic values than those in the main body of the lake. The $\delta^{13}C$ value of DIC increases slightly from south to north in the lower lake. Moreover, the data at sites U_2, U_1, and L_1 suggest that during summer DIC is more enriched in ^{13}C than in winter.

$\delta^{18}O$ H_2O

Spring water has a $\delta^{18}O$ value of -7.56‰ . In the lower lake there is an increase from the spring value of -7.56‰ to -3.63‰ at the north end. In the upper lake the reverse in true; $\delta^{18}O$ increases slightly from site U_2 to U_1.

Carbonate in lake bottom sediment

There is little temporal or spatial change in the isotope composition of carbonate bottom sediments in the lower lake (with respect to carbon and oxygen). The upper lake has larger isotopic values by approximately 1‰. Comparing 1993 samples and those taken in 1994 (sites L_2 and L_3) it can be seen that there was little change over the course of the year. Although carbonate sediments were not analyzed at any other time of the year it is not thought that they would change significantly (see discussion below).

Calculated carbonate precipitate isotopic values

There was insufficient carbonate suspended in the water column to measure actual $\delta^{13}C$ and $\delta^{18}O$ values. However, using the data collected it was possible to calculate the expected isotopic composition of a carbonate precipitate. These expected values are shown in the last two columns of Table 3.

The expected $\delta^{13}C$ of the precipitate (ppt) was calculated assuming a +1.3‰ fractionation between dissolved HCO_3^- (measured DIC) and solid $CaCO_3$ (ppt) as described by Emrich *et al.* (1970). Thus the calculated $\delta^{13}C$ ppt is simply 1.3‰ larger than the measured $\delta^{13}C$ DIC.

The expected $\delta^{18}O$ ppt was calculated using the palaeotemperature equation (Hays and Grossman, 1991 revised from O'Neil *et al.*, 1969):

$$T(^{\circ}C) = 15.7 - 4.36(\delta c - \delta w) + 0.12(\delta c - \delta w)^2,$$

Where δc is the $\delta^{18}O$ of carbonate relative to PDB and δw is the $\delta^{18}O$ of water relative to SMOW. Given that δw (ie. $\delta^{18}O_{H2O}$) and temperature are known, δc (ie. $\delta^{13}C_{ppt}$) can be calculated. For the purposes of the calculation the temperature was taken to be 15°C as this is a best estimate of water temperature at the time of expected maximum precipitation in early spring (i.e. associated with any spring photosynthetic activity).

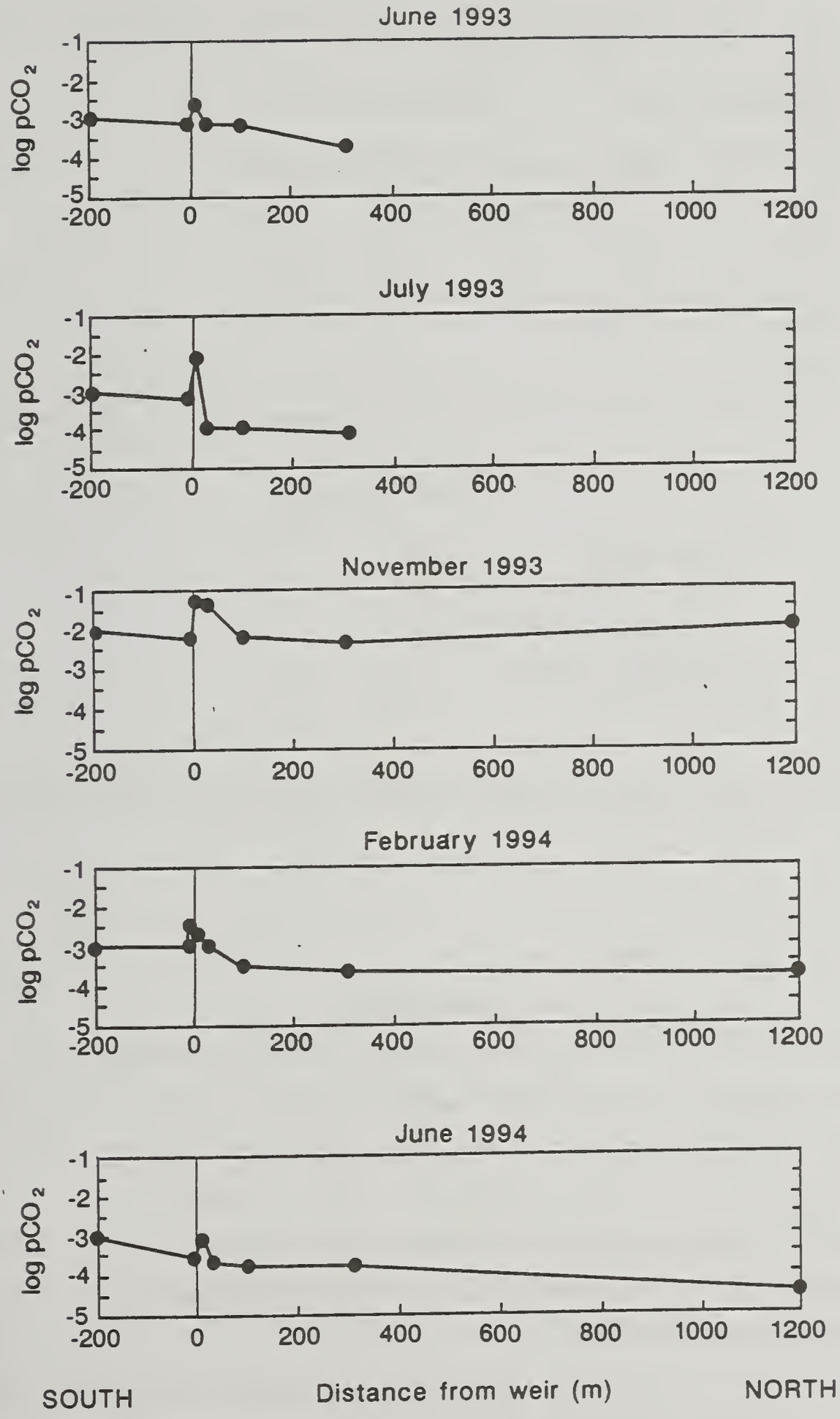

Fig. 6. Plot of concentration (partial pressure) of carbon dioxide versus distance from the weir for various sample dates, Holkham Lake.

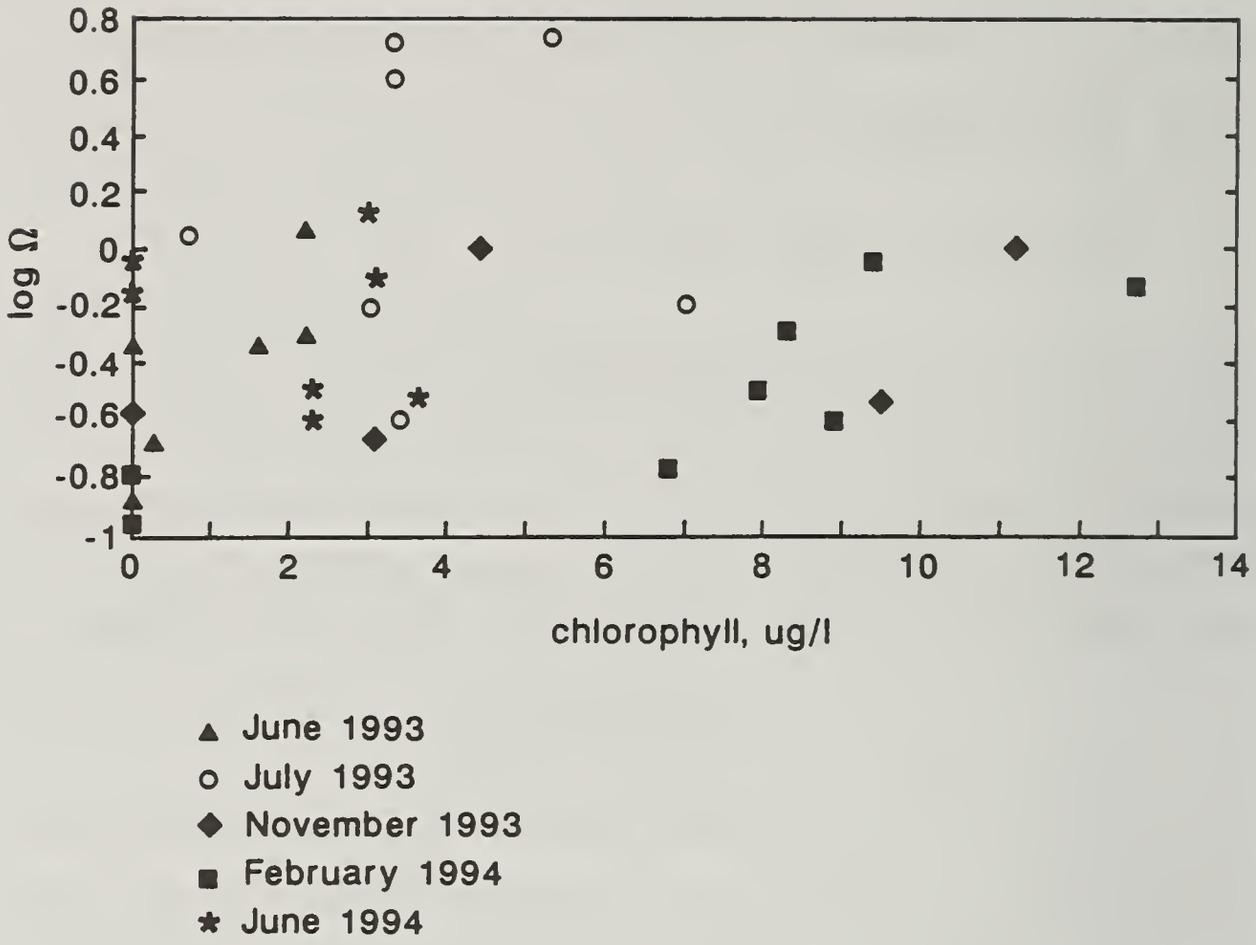

Fig. 7. Plot of log $\Omega_{calcite}$ versus chlorophyll for various sample dates, Holkham Lake.

DISCUSSION

Between June 1993 and June 1994 no vaterite was found in Holkham Lake. This finding is significant because Holkham Lake has been cited widely as an example of natural, lacustrine vaterite precipitation (for example in Nathan, 1971; Jones and Bowser, 1978 and Friedman and Schultz, 1994a). Because this study has not reproduced the results of Rowlands and Webster (1971) it does not support their finding that Holkham Lake is an example of natural lacustrine vaterite precipitation. There are three possible reasons for this.

Firstly it is possible that the findings of Rowlands and Webster were wrong because they misinterpreted their XRD and electron microscopy results. Unfortunately neither of the authors could be contacted and therefore a detailed copy of their results is unavailable for inspection.

Table 3: Measured and calculated isotope data from Holkham Lake

Site(date)	MEASURED(‰)[1]			CALCULATED(‰)[2]		
	$\delta^{13}C_{DIC}$	$\delta^{18}O_{H2O}$	$\delta^{13}C_{sed}$	$\delta^{18}O_{sed}$	$\delta^{13}C_{ppt}$	$\delta^{18}O_{ppt}$[3]
U_2						
18.6.93	-11.03	---	-3.86	-5.37	-9.73	
4.11.93	-11.82	-6.41	---	---	-10.52	-6.25
U_1						
18.6.93	-10.61	---	---	--	-9.31	---
4.11.93	-11.22	-6.50	---	---	-9.92	---
Spr. 2						
18.6.93	-14.80	---	---	---	-13.50	---
2 4.11.93	-14.65	-7.56	---	---	-13.35	---
L_1						
18.6.93	-11.35	---	-4.98	-5.88	-10.05	
4.11.93	-13.66	-6.27	---	---	-12.36	-6.11
L_2						
18.6.93	-11.75	---	-4.46	-5.91	-10.45	---
4.11.93	-11.41	---	---	---	-10.31	---
14.6.94	---	---	-4.84	-5.89	---	---
L_3						
18.6.93	-10.93	---	-4.87	-5.80	-9.63	
4.11.93	---	-4.71	---	---	---	-4.55
14.6.94	---	---	-4.67	-5.93	---	
N.E.						
4.11.93	-11.06	-3.63	---	---	-9.76	---

[1] All measured values relative to VPDB scale except $\delta^{18}O$ H_2O which is relative to VSMOW scale.

[2] Where subscript "ppt" denotes carbonate precipitate

[3] The calculated value for $\delta^{18}O_{ppt}$ refers to the site specified rather than a particular time of sampling at that site.

Secondly, this study may be in error. However, none of the parameters measured in the field or in the laboratory produced ambiguous results. There is no reason to doubt the reliability of the XRD analyses or the way in which the samples were collected and prepared for analysis. Solids collected from filters were neither ground or heated (avoiding possible transformation of metastable vaterite to calcite) and in the case of sample L_1 (June 1994) analysis was conducted within five hours of sampling. The results of this study are quite self-supportive and in many ways resemble a similar study of freshwater carbonate chemistry by Michaelis *et al.* (1985).

If neither Rowlands and Webster nor this study are in error then either the hydrochemistry of the lake has changed such that vaterite no longer precipitates, or the conditions needed for vaterite precipitation are unusual and sporadic in occurrence. Comparison of an unpublished report by Rowlands and Webster (1970) with field observations in 1993-94 reveals that generally there has been little change in the lake environment. The size and shape of the lake, use of neighbouring land and even the basic water chemistry characteristics show only minor differences. For example, the pH at the spring has remained at about 7.2, while pH rises to about 9 at the north end of the lake during the summer. Also the lake still takes on a milky (opalescent) appearance from time to time (although to a lesser extent in recent years). Even in June 1994 the lower lake was cloudy, in contrast to the very clear upper lake.

There have, however, been some changes at Holkham Lake over the last 23 years. Perhaps most noticeably groundwater now seems to discharge into the lake at different sites. Rowlands and Webster identified five springs distributed quite evenly along the south bank of the upper lake and a further two in the lower lake about 50 m and 100 m from the weir on the east bank. In June 1970 it was the upper lake that was reported to be most milky; however, in June 1994 it was the lower lake that had the more cloudy appearance. Furthermore in June 1970 the whole lake was supersaturated with respect to calcite. By contrast, in this study only in July 1993 was the lake supersaturated and even then only in the lower lake where there was no evidence of $CaCO_3$ precipitation (Fig. 2).

Rowlands and Webster quoted a pH of 8.5 in the upper lake which compares to 7.5-8.0 in June and July 1993 (Fig. 5). Higher pH might suggest more intense biological activity as CO_2 is removed from the water column by plants (Fig. 6). If pH is high then CO_3^{2-} becomes the more important species of dissolved carbonate in the water column

producing more favourable conditions for $CaCO_3$ precipitation. Rowlands and Webster suggested that vaterite precipitation is seeded by extreme local pH variations close to growing benthic plants. There is the possibility that in 1970 peculiar conditions of very active photosynthesis, carbon dioxide removal, high pH, high alkalinity and therefore a high degree of supersaturation caused vaterite to precipitate.

In July 1993 at site L_1, high pH coincided with high Ω values and relatively high alkalinity (Figs. 5, 2 and 4 respectively), yet no carbonate mineral was present in the water column. This may have been due to a low Ca^{2+} concentration (Fig. 3).

Although there have been marked occurrences of whitings in the lake during years other than 1970 these have not occurred in recent spring seasons. This may be because the lower lake was dredged of plants along half of its length a few years ago. However, the only time that the lake was observed to be cloudy during this study was in June 1994 in the lower (less plant-rich) lake. At this time the upper lake was very densely populated with benthic plants and algae and the water was very clear. This observation suggests further that factors other than photosynthesis are required for $CaCO_3$ precipitation.

There was no evidence of any pollution in the form of foaming or oily film on the water (in either 1970 or 1993-94); however, phosphate concentrations (up to 398 μg^{-1}, Table 2) are high. It is probable that most of this phosphate comes from the dissolution of guano, deposited directly into the lake by the large bird population. R. Boar (pers. comm.), considers phosphate concentrations >50 μg^{-1}, unusually large for Norfolk lakes, and Nathan (1971) suggested that phosphate may be a factor which encourages vaterite precipitation in Holkham Lake. Since phosphate is an important plant nutrient it might be expected that higher phosphate concentrations would contribute to more active photosynthesis and therefore to the above-mentioned favourable conditions for supersaturation with respect to $CaCO_3$.

A final consideration is how the Mg/Ca ratio of the water can affect the form of carbonate precipitated in the lake. Müller *et al.* (1972) showed that the Mg/Ca ratio is the main factor governing whether calcite, aragonite, Mg-calcite or dolomite precipitate. If Mg/Ca < 2 then only low Mg-calcite is precipitated. For aragonite to precipitate, the Mg/Ca must be greater than 12. Table 2 shows that in Holkham Lake the Mg/Ca < 0.15

and therefore, according to Müller *et al.* (1972) a carbonate mineral other than calcite is unlikely to precipitate.

Stable Isotopes

$\delta^{13}C_{DIC}$

$\delta^{13}C_{DIC}$ was lowest at the spring (-14.8‰). Using a mass balance equation it was calculated that 90% of this DIC is from a (soil) organic matter source (assuming that DIC in spring water is derived exclusively from a mixture of decaying soil organic matter and dissolving chalk bedrock). The mass balance equation assumes that pure organically derived DIC has a $\delta^{13}C$ of -16.5‰ (Andrews *et al.*, 1993) and chalk bedrock in north Norfolk has a $\delta^{13}C$ of 1.5‰ (Jenkyns *et al.*, 1994 and Scholle and Arthur, 1980).

Table 3 shows that between the spring and site L_1 there is a sharp increase in $\delta^{13}C_{DIC}$ which may occur because of the dissolution of chalk bedrock with a relatively large $\delta^{13}C$ composition. However, the presence of platy carbonate sediments within a few metres of the spring suggest that carbonate minerals are being precipitated rather than being dissolved. The most probable reason for the increase in $\delta^{13}C_{DIC}$ is associated with degassing of CO_2 at the spring (Fig. 6). The isotopically lighter and more reactive ^{12}C is preferentially degassed leaving the DIC enriched in ^{13}C. At the spring there will also be a certain degree of mixing with atmospheric CO_2 ($\delta^{13}C$ = -7‰) as the water entrains air. This also would cause enrichment of DIC in ^{13}C causing an increase in $\delta^{13}C_{DIC}$.

The difference in $\delta^{13}C$ between the spring and the main body of the lake is approximately +3.5‰. This difference occured closer to the point of spring discharge in June than in November, because in November the spring had a higher discharge. Pentecost (1981) found that the effects of degassing and bubbling at a spring need not be restricted to the immediate locality. This was seen in Holkham Lake when site L_1 was sampled in November. Despite being 30m from the spring it was still isotopically influenced by the spring as it had a low $\delta^{13}C_{DIC}$.

Table 3 indicates that the $\delta^{13}C_{DIC}$ continues to increase along the whole length of the lower lake. There are three possible reasons for this:

Firstly, the water may be dissolving isotopically heavy chalk from the lake bed ($\delta^{13}C_{DIC}$ = 1.5‰) as it travels northwards - therefore becoming enriched in ^{13}C. From the discussion below this is unlikely since the carbonate bottom sediment is dominantly water column precipitate and lake water does not come into significant contact with chalk bedrock.

Secondly, the enrichment in ^{13}C may be due to preferential removal of ^{12}C by primary production. Evidence from sites U_2, U_1 and L_1 show that the lake is relatively more enriched in ^{13}C in June than in November. From a biological point of view this would be expected. In the spring and summer months, increased photosynthesis preferentially removes ^{12}C and therefore $\delta^{13}C_{DIC}$ increases. During winter, organic matter decay releases isotopically light carbon into the water column, decreasing $\delta^{13}C_{DIC}$. However, if lake biology were the sole influence on $\delta^{13}C_{DIC}$, it would be expected that in November the decay of organic matter and resulting release of isotopically light carbon into the water column would cause the $\delta^{13}C_{DIC}$ to fall - yet from Table 3 it appears to increase. There must, therefore, be another factor involved.

The third factor to consider is the effect of wind action on the lake. This occurs throughout the year producing a constant mixing with atmospheric CO_2 ($\delta^{13}C$ = -7‰) which would cause an enrichment in ^{13}C. The $\delta^{18}O_{H2O}$ data discussed below support this by showing evidence of evaporative effects in the lower lake. Given that there is a +9.5‰ fractionation between $HCO_3^-{}_{(aq)}$ and $CO_{2(g)}$ at 10°C (Emrich *et al.*, 1970), DIC in equilibrium with atmospheric CO_2 would have a $\delta^{13}C$ of +2.5‰. Neither the upper lake nor the lower lake have water residence times long enough for complete equilibrium with atmospheric CO_2 to occur, but it is interesting to note where and when the highest $\delta^{13}C_{DIC}$ was recorded. This occurred in the upper lake (site U_1) where the residence time of water appears to be relatively high (indicated by low flow over the weir) and during sampling on 16.6.93 which was the windiest of the five visits to Holkham Lake. Both of these factors make mixing with atmospheric CO_2 more favourable.

$\delta^{18}O_{H2O}$

Table 3 shows that $\delta^{18}O_{H2O}$ increases from the spring northwards along the lower lake. This is probably caused by the lighter ^{16}O being preferentially evaporated leaving the water relatively more enriched in ^{18}O as it travels north.

Carbonate in Lake-bed Sediment

There is little change in $\delta^{13}C_{sed}$ and $\delta^{18}O_{sed}$ of the sediment over the course of a year (Table 3). This is because the sediment on the lake floor has accumulated over a period of years. Therefore its isotopic composition represents a longer term average value. From the evidence available there is also little change in $\delta^{13}C_{sed}$ and $\delta^{18}O_{sed}$ between sites L_1 and L_3. Perhaps the change in $\delta^{13}C_{DIC}$ along the lake is not enough to significantly affect the isotopic value of the sediment.

From Table 3 it can be seen that in the upper lake $\delta^{13}C_{sed}$ is approximately 1‰ higher, and $\delta^{18}O$ sed 0.5‰ higher, than in the lower lake. However, $\delta^{13}C_{DIC}$ and $\delta^{18}O_{H2O}$ in the upper lake are not very different from those of the lower lake. Table 4 shows that the differing isotopic compositions in carbonate sediment throughout the lake are because of the changing proportions of water column precipitate to chalk bedrock that makes up the sediment; a higher proportion of chalk enriching the sediment in ^{13}C.

Table 4 shows that when calculated from carbon isotope data the predicted ratio of precipitate to chalk in the sediment is about 1:1. However, when calculated from oxygen isotope data the sediment is shown to be dominated by water column precipitate. The mixing ratios predicted on the basis of the oxygen data are more reliable because oxygen isotopes are more robust to most lake processes. $\delta^{13}C$ is more variable in Holkham Lake as Figure 8 shows. Stuiver (1970) explains that during photosynthesis plants preferentially metabolise $^{12}CO_2$ therefore leaving the water enriched in ^{13}C. At Holkham Lake it is inferred that the times of maximum photosynthetic activity are associated with times of maximum carbonate precipitation. It is therefore expected that when most carbonate is precipitated, DIC in the water is enriched in ^{13}C which produces a precipitate that is similarly enriched in ^{13}C.

The problem with the mixing ratios calculated from the carbon isotope data collected on the five visits to Holkham Lake is that $\delta^{13}C_{DIC}$ was never measured during a photosynthetic 'bloom' event. Therefore the predicted $\delta^{13}C_{ppt}$ values (which were

calculated from $\delta^{13}C_{DIC}$ at 'non-bloom times') are too low. This gives the impression that the sediment has a greater chalk content than it actually has (Fig. 8). The fractionation in $\delta^{13}C_{DIC}$ of lake waters caused by 'bloom' events is reported to be about 5‰ (Stuiver, 1970). Taking this into account, revised mixing ratios based on the carbon data were calculated (Table 4), and are similar to those calculated from oxygen isotope data.

Figure 8 shows graphically how misleading the unrevised carbon isotope data can be when considering the proportional amounts of water column precipitate and chalk in the sediment. It shows that the dominant component of lake-bed sediment is water column precipitate.

Table 4: Ratio of precipitate to chalk bedrock in carbonate sediments at three sites. Calculated by using both carbon and oxygen isotope data (all values relative to VPDB)

Sample	$\delta^{13}C$				$\delta^{18}O$				$\delta^{13}C$
	Sed	ppt[1]	chalk[2]	ratio[3]	Sed	ppt	chalk[2]	ratio[3]	revised[4]
U_2	-3.86	-10.13	1.5	46:54	-5.37	-6.25	-2.0	79:21	82:18
L_1	-4.98	-11.21	1.5	51:49	-5.88	-6.11	-2.0	94:68	4:16
L_3	-4.65	-10.38	1.5	52:48	-5.87	-4.55	-2.0	---	89:11

[1] Where more than one value for the site, the mean is taken.
[2] Mean carbon and oxygen isotope values for north Norfolk bedrock from Jenkyns *et al.*, (1994) and Scholle and Arthur (1980).
[3] Ratios calculated using mass balance equations:

$$\delta^{13}C_{sed} = a.\ \delta^{13}C_{ppt} + b.\delta^{13}C \text{ chalk}$$

$$\delta^{18}O_{sed} = a.\ \delta^{18}O_{ppt} + b.\ \delta^{18}O \text{ chalk} \qquad \text{where: } a + b = 1$$

[4] Based on Stuiver's (1970) findings that $CaCO_3$ precipitate can be enriched by about 5‰ because of photosynthesis

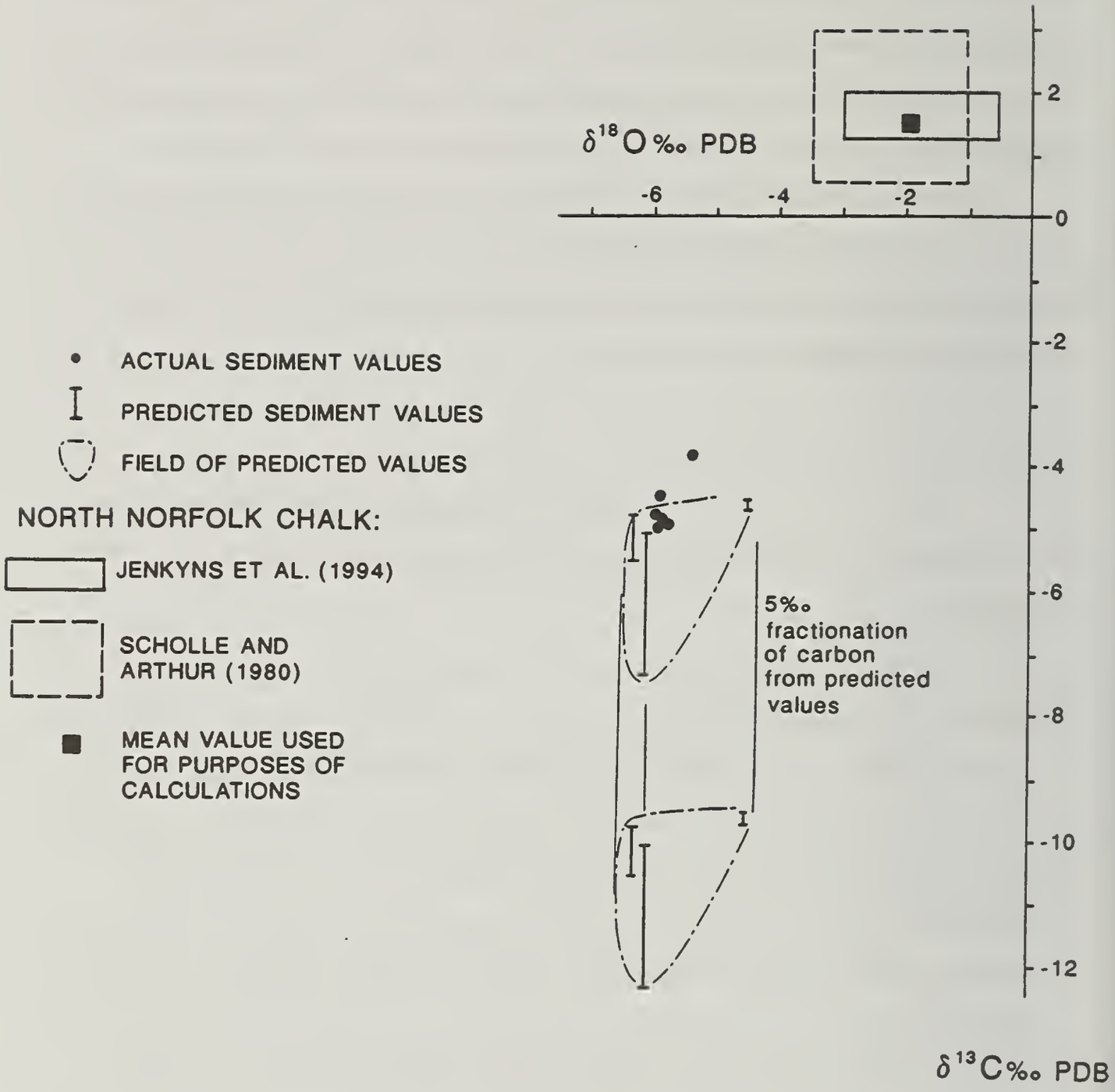

Fig. 8. Carbon and oxygen isotope data for the sediment samples shown in Table 3, compared with predicted precipitate and actual north Norfolk chalk isotopic values.

CONCLUSIONS

Firstly, no vaterite was found in Holkham Lake. The only water column carbonate precipitate identified between June 1993 and June 1994 was calcite. This is a significant result because Holkham Lake has been cited as the world's only example of natural vaterite precipitation. Even during the writing of this report two papers have referred to it (Kralj *et al.*, 1994 and Friedman and Schultz, 1994b). There is no obvious reason why vaterite should precipitate at Holkham Lake. Indeed, the carbonate chemistry of the lake is not dissimilar to other carbonate rich waters (for example Michaelis *et al.*, 1985). Müller *et al.* (1972) consider the Mg/Ca ratio as the governing factor on formation of particular carbonate minerals in lacustrine environments. Comparing their findings to the situation at Holkham Lake it would be highly unlikely that anything other than calcite would precipitate.

Secondly, there are two main influences on the carbon isotope chemistry in the lake. Photosynthetic activity is probably an influence and this is probably seasonal. During intense photosynthesis the water is enriched in ^{13}C, probably by approximately 5‰. The other influence is that of wind action on the lake surface which mixes atmospheric CO_2 into lake waters. This occurs throughout the year.

Thirdly, carbonate in the lake sediment consists predominantly (over 90%) of calcite precipitated from the water column and probably associated with photosynthetic activity in the spring and summer. Chalk bedrock contributes very little to the sediment and therefore has little influence on the lake water as it travels from the spring to the weir at the north end.

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REFERENCES

ALBRIGHT, J.N. 1971 Vaterite stability. *The American Mineralogist*, **56**, 620-624.

ANDREWS, J.E., RIDING, R. and DENNIS, P.F. 1993 Stable isotopic compositions of recent freshwater cyanobacterial carbonates from the British Isles: local and regional environmental controls. *Sedimentology*, **40**, 303-314.

APPELO, C.A.J. 1988 *A computer program for equilibrium calculations for water analysis*. Institute voor Aardwetenschappen, Vrije Universiteit, Amsterdam.

ARTHUR, M.A., ANDERSON, T.F., KAPLAN, I.R. and LAND, L.S. 1983 *Stable Isotopes in Sedimentary Geology* Society of Economic Paleontologists and Mineralogists, Short Course notes No. 10. Tulsa.

BENTNOR, Y.K. 1963 Some unusual minerals from the "Mottled Zone" Complex, Israel. *American Mineralogist*, **48**, 924-930.

BISHOP, P.K. 1990 Precipitation of dissolved carbonate species from natural waters for $\delta^{13}C$ analysis - a critical appraisal. *Chemical Geology (Isotope Geoscience Science)*, **80**, 251-259.

CARLSON, W.D. 1983 The Polymorphs of $CaCO_3$ and the Aragonite-Calcite Transformation. Chapter 6. In: Reeder R.J., *Carbonates: Mineralogy and Chemistry*. Reviews in Mineralogy 11. p. 191-225. Mineralogical Society of America. Chelsea.

EMRICH, K., ERHALT, D.H. and VOGEL, J.C. 1970 Carbon isotope fractionation during precipitation of calcium carbonate. *Earth and Planetary Science Letters*, **8**, 363-371.

EPSTEIN, S. and MAYEDA, T. 1953 Variation of ^{18}O content of waters from natural sources. *Geochimica Cosmochimica et Acta*, **4**, 213-224.

FAURE, G. 1977 *Principles of Isotope Geology*, John Wiley & Son. New York.

FRIEDMAN, G.M., SCHULTZ, D.J., GUO, B. and SANDERS, J.E. 1993 Vaterite (an uncommon polymorph of $CaCO_3$): occurrences in boreholes demonstrate unexpected longevity. *Journal of Sedimentary Petrology*, **63**, 663-664.

FRIEDMAN, G.M., and SCHULTZ, D.J. 1994a Vaterite (an uncommon polymorph of $CaCO_3$): occurrences in boreholes demonstrate unexpected longevity - reply. *Journal of Sedimentary Research* , **A64,** 419.

FRIEDMAN, G.M., and SCHULTZ, D.J. 1994b Precipitation of vaterite ($CaCO_3$) during oil-field drilling. *Mineralogical Magazine,* **58**, (392), 401-408.

HAYS, P.D. and GROSSMAN, E.L. 1991 Oxygen isotopes in meteoric calcite sediments as indicators of continental paleoclimate. *Geology*, **19**, 441-444.

JENKYNS, H.C., GALE, A.S. and CORFIELD, R.M. 1994 Carbon and oxygen isotope stratigraphy of the English Chalk and Italian scaglia and its paleoclimatic significance. *Geological Magazine*, **131**, 1-34.

JONES, B.F. and BOWSER, C.J. 1978 The mineralogy and related chemistry of lake sediments. In: Lerman, A. (ed.), *Lakes Chemistry, Geology, Physics*, 195-235, Springer-Verlag, New York.

KELTS, K. and HSÜ, K.J. 1978 Freshwater carbonate sedimentation, Chapter 6. In: Lerman, A. (ed.) *Lakes, Chemistry, Geology and Physics*. Springer-Verlag, New York.

KLEINER, J. 1988 Coprecipitation of phosphate with calcite in lake water: A laboratory experiment modeling phosphorus removal with calcite in Lake Constance. *Water Research,* **22**, 1259-1265.

KRALJ, D., BRECEVIC, L. and NIELSEN, A.E. 1994 Vaterite growth and dissolution in aqueous-solution. 2. Kinetics of dissolution. *Journal of Crystal Growth*, **143**, 269-276.

LIPPMANN, F. 1973 *Sedimentary Carbonate Minerals,* Springer-Verlag. Berlin

MAYER, F.K. and WEINECK, 1932 Die Vertreitung des Kalzium-karbonat im Tierreich unter besonderer Berücksichtigung der Wirbellosen. Jena. z. Naturwiss. 66(59), 199-222.

McCONNELL, J.D.C. 1960 Vaterite from Ballycraigy, Larne, Northern Ireland. *Mineralogical Magazine*, **32**, 535-544.

MEIGEN, W. 1911 Uber Kohlensauren Kalk *Verhandl. Ges. Deyt. Naturforsch. Arzte* 82,II(1), 120-124.

MENGARD, R.O. 1968 Planktonic Photosynthesis and the Environment of Carbonate Deposition in Lakes. University of Minnesota Limnology Research Center. Interim Report **2**, 47pp.

MICHAELIS, J., USDOWSKI, E. and MENSCHEL, G. 1985 Partitioning of ^{13}C and ^{12}C on the degassing of CO_2 and the precipitation of calcite - Rayleigh-type fractionation and a kinetic model. *American Journal of Science,* **285**, 318-327.

MÜLLER, G., IRION, G. and FÖRSTNER, U. 1972 Formation and diagenesis of inorganic Ca-Mg carbonates in the lacustrine environment. *Naturwissenschaften* 59(4), 158-164.

MURPHY, J. and RILEY, J.P. 1962 A modified single solution method for the determination of phosphate in natural waters. *Analytica Chimica Acta*, **27**, 31-36.

NATHAN, C.C. 1971 Vaterite in lake water. *Nature Physical Science,* **231**, 158.

NORTHWOOD, D.D. and LEWIS, D. 1968 Transformation of vaterite to calcite during grinding. *American Mineralogist,* **53**, 2089-2092.

O'NEIL, J.R., CLAYTON, R.N. and MAYEDA, T.K. 1969 Oxygen isotope fractionation in divalent metal carbonates. *Journal of Chemical Physics,* **51**, 5547-5558.

PARSONS, T.R., MAITA, Y. and LALLI, C.M., 1984 *A Manual of Chemical and Biological Methods for Seawater Analysis,* Pergamon Press. Oxford.

PEARSON, F.J. and COPLEN, T.B. 1978 Stable isotope studies of lakes. Chapter 10. In: Lerman, A. (ed.), *Lakes, Chemistry, Geology and Physics*, Springer-Verlag, New York.

PENTECOST, A. 1981 The tufa deposits of the Malham district, North Yorkshire. *Field Studies*, **5**, 365-387.

ROWLANDS, D.L.G. and WEBSTER, R.K. 1971 Precipitation of vaterite in lake water. *Nature Physical Science,* **229**, 158.

SCHOLLE, P.A. and ARTHUR, M 1980 Carbon isotope fluctuations in Cretaceous pelagic limestones: potential stratigraphic and petroleum exploration tool. *The American. Association of Petroleum Geologists Bulletin,* **64**, 67-87.

SCOFFIN, T.P. 1987 *An Introduction to Carbonate Sediments and Rocks*, Blackie & Son Ltd. Glasgow

STUIVER, M. 1970 Oxygen and carbon isotope ratios of fresh-water carbonates as climatic indicators. *Journal of Geophysical Research,* **75**, 5247-5257.

SUTOR, D.J. and WOOLEY, S.E. 1967 Gallstones of unusual composition: calcite, aragonite and vaterite. *Science,* **159**, 1113-1114.

TALBOT, M.R. 1990 A review of the palaeohydrological interpretation of carbon and oxygen isotopic ratios in primary lacustrine carbonates, *Chemical Geology (Isotope Geoscience Section),* **80**, 261-279.

TUCKER, M.E. and WRIGHT, V.P. 1990 *Carbonate Sedimentology*, Blackwell Scientific Publications. Oxford.

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The Geological Society of Norfolk exists to promote the study and understanding of geology, particularly in East Anglia, and holds monthly meetings throughout the year.

Visitors are welcome to attend meetings and may apply for membership of the society. For further details write to The Secretary, Geological Society of Norfolk, Castle Museum, Norwich NR1 3JU.

Copies of the Bulletin may be obtained from the Secretary at the address given above; it is issued free to members.

The illustration on the front cover is figure 5 from J. McArthur's article in this issue of the Bulletin. It shows a comparison of strontium isotopes in the Norfolk Chalk and Chalk of the US western interior.

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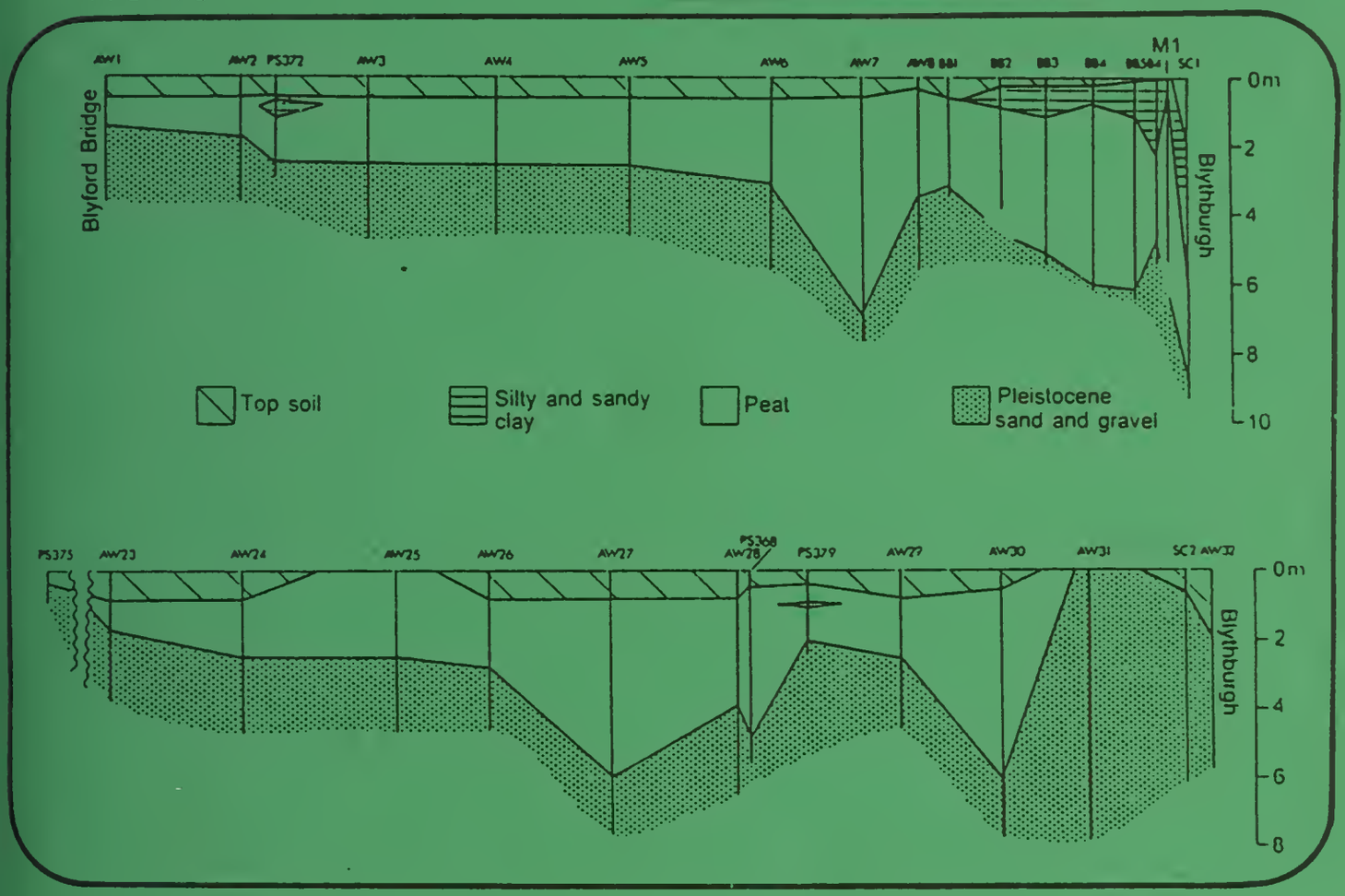

PUBLISHED 1996

CONTENTS INCLUDE

Palaeoecology, Palaeoenvironment and Stratigraphy of Upper Campanian Chalk in East Norfolk

Holocene Vegetation and Salinity Change, Blyth Estuary, Suffolk.

BULLETIN OF THE GEOLOGICAL SOCIETY OF NORFOLK

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Editor: Julian E. Andrews

School of Environmental Sciences,
University of East Anglia,
Norwich NR4 7TJ

Telephone 01603 592536
FAX 01603 507719
E-mail J.Andrews@uea.ac.uk

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EDITORIAL

While Bulletin No. 43. is well behind official publication date, the material in this issue has been reviewed, edited and gone to press within 8 months of initial receipt.

This issue has a palaeoenvironmental and palaeoecological flavour. Paul Whittlesea has contributed two associated papers which describe the stratigraphic position, palaeoecology and palaeoenvironment of two temporary Chalk exposures in the Norwich area. David Brew and his co-workers concentrate on the Holocene environmental history of the estuarine River Blyth in Suffolk. Their work is timely given the current political and economic interest in the way coastal environments respond to sealevel change.

I am still short of material for future issues and welcome the submission of papers on any aspect of East Anglian geology. My intention is to publish a series of 50 page Bulletins in fairly rapid succession to catch up on the publication schedule.

INSTRUCTIONS TO AUTHORS

If possible, contributors should submit manuscripts as word-processor print out accompanied by a disk copy. We can handle most word-processing formats although PC Word, WordPerfect or ASCII files are preferred. In addition we accept typewritten copy and will consider legible handwritten material.

It is important that the style of the paper, in terms of overall format, capitalisation, punctuation, etc. conforms as strictly as possible to that used in Vol. 41 of the Bulletin. Titles and first order headings should be capitalised, centred and in bold print. Second order headings should be centred, bold and lower case. Text should be 1½ line spaced. All measurements should be given in metric units.

References should be arranged alphabetically in the following style.

BALSON, P.S. & CAMERON, T.T.J. 1985. Quaternary mapping offshore East Anglia. *Modern Geology*, **9**, 221-239

STEERS, J.A. 1960. Physiography and evolution: the physiography and evolution of Scolt Head Island. In Steers, J.D. (ed.) *Scolt Head Island* (2nd ed.), 12-66, Heffer, Cambridge.

BLACK, R.M. 1988. *The Elements of Palaeontology*. 2nd Ed., Cambridge University Press, Cambridge. 404pp.

Illustrations should be drawn with thin dense black ink lines. Thick lines, close stipple or patches of solid black should be avoided as these spread in printing. Original illustrations should, before reproduction, be not more than **175mm by 255mm**. Full use should be made of the first (horizontal) dimension which corresponds to the width of print on the page, but the second (vertical) dimension is an upper limit only. Half tone photographic plates are acceptable when their use is warranted by the subject matter, provided the originals exhibit good contrast.

The editors welcome original research papers, notes or comments, and review articles relevant to the geology of **East Anglia** as a whole, and do not restrict consideration to articles covering Norfolk alone. All papers are independently refereed by at least one reviewer.

TEMPORARY CHALK EXPOSURES IN EAST NORFOLK, (UPPER CAMPANIAN, ZONE OF *Belemnitella mucronata sensu lato*) 1989-90.

Paul S. Whittlesea

8 Eaton Old Hall, Hurd Road,
Norwich, NR4 7BE

ABSTRACT

The results of investigating two temporary Chalk sections at Drayton and Whitlingham (near Norwich) are reported. Results from Drayton confirmed the expected stratigraphic position and improved knowledge of the fauna in these beds. Integrating the Whitlingham exposure into the local Chalk stratigraphy required a reassessment of data obtained from other temporary sections in the vicinity, several of which were in glacial erratics. It is now concluded that the Whitlingham section exposed the youngest beds of the Paramoudra-1 division of the ***mucronata*** *zone. No extant section exposes the whole of these beds. Fossils recovered from this site substantially improve previous knowledge of the fauna in these beds. Both sites produced samples that yielded new invertebrate species (not described formally here) together with further specimens of some rare taxa known previously only from their holotypes.*

INTRODUCTION

The part of the Chalk that in Norfolk has been traditionally assigned to the zone of *Belemnitella mucronata sensu lato* is divisible into at least three zones using belemnites belonging to the genus *Belemnitella*. In western Europe the sequence is, in ascending order: *B. mucronata sensu stricto*, *B. minor*, and *B. langei*. Unfortunately, there is a long history of nomenclatural confusion associated with these taxa that only recent statistical analysis of samples of topotype populations has begun to unravel (Christensen, 1975, Christensen, 1995). The result has been that some British authors have refrained from using the more refined stratigraphical framework in the hope of avoiding further confusion

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Recent research on belemnite samples from the "*mucronata*" horizon in Norfolk (Christensen, 1995) provides an accurate local belemnite biostratigraphy with which to work, though some taxonomic difficulties remain, especially with respect to *B. langei* the type locality of which is unknown.

Currently, the most important exposures in the upper Upper Campanian zone of *Belemnitella mucronata* of eastern Norfolk are the outcrops in the cliffs and on the foreshore of the north Norfolk coast between Weybourne Hope and Cromer. There are no natural exposures inland and there is now only one major working quarry (at Caistor St. Edmund, to the south of Norwich (Fig. 1). Between them these expose only about 60% of the zone in the middle of the succession, primarily the Weybourne Chalk, Catton Sponge Beds and Beeston Chalk together with the lower third of the Paramoudra Chalk (Peake and Hancock, 1961, 1970).

This paper describes two temporary exposures in the *mucronata* zone at Drayton (Fig.1) and at Whitlingham (Fig. 1) that became available for study during 1989-90. The exposure at Drayton proved to be in the Pre-Weybourne-2 Chalk and that at Whitlingham in the uppermost Paramoudra-1 Chalk thereby providing an opportunity to study part of the succession which is normally inaccessible. Table 1 details the Upper Campanian - Lower Maastrichtain Chalk stratigraphy in Norfolk.

COLLECTING METHODS AND PREPARATION TECHNIQUES

Besides searching for macro-fossils in the field, several 5-10kg sediment samples were collected from each site for subsequent investigation. Processing of bulk sediment samples is an indispensable technique if a thorough understanding of the fauna at each horizon is to be gained. Owing to the scarcity of collecting opportunities at some horizons, it is the author's practice to try to recover at least a thousand specimens from temporary sites, although fewer specimens are sufficient for most biostratigraphical purposes that rely on statistical techniques.

Samples were mechanically disaggregated by first soaking them in water to soften them, then gently crushed with a wooden pestle in a 1mm sieve immersed in a bowl of water, which acted as the mortar. This avoided producing large quantities of dust associated with dry preparation and simultaneously aided separation of fossils from the sediment as it softens.

Fig. 1. Locality map showing relative positions of sites mentioned in the text

Table 1: High Campanian / Maastrichtian Chalk Stratigraphy of Norfolk

Lower Maastrichtian

Grey Beds (including Tuffeau)
White chalk with *Liostrea lunata*
White chalk without *Liostrea lunata*
Sponge Beds
Porosphaera Beds
Pre-*Porosphaera* Beds

Campanian/Maastrichtian Boundary

Pyramidata hardground

Upper Campanian ("*mucronata*" Chalk of authors)

Paramoudra-2
Paramoudra-1
Beeston
Catton Sponge Beds
Weybourne-3
Weybourne-2
Weybourne-1
Pre-Weybourne-5
Pre-Weybourne-4
Pre-Weybourne-3
Pre-Weybourne-2
Pre-Weybourne-1

The rock was not rubbed through the sieve as this can severely abrade surface detail on specimens, frustrating subsequent attempts to identify them. Any specimens noticed as the chalk disaggregated were removed and treated individually to reduce fragmentation.

The residue was washed and dried before division into $1cm^3$ aliquots which were examined at low magnification under a stereoscopic microscope. All fossils, whether fragmentary or complete were picked from the residue. Prior to identification some specimens were cleaned further in an ultrasonic tank (indispensable when dealing with bryozoa and the many other tiny forms found). Where possible, all specimens were then determined to species level and their numbers recorded for subsequent analysis.

A rough note was made of the yield from the samples; owing to lack of access to a laboratory with an accurate balance it was not possible to measure precisely the percent

yield by weight. However, this is adjudged always to be less than 1% by weight and usually less than 0.1%.

Appendices 1 and 2 detail numbers of specimens recovered from a sample. A specimen comprises not just complete specimens but any substantial identifiable skeletal component. For example, disarticulated brachiopod shells, isolated asteroid ossicles and individual echinoderm test fragments and spines all count as "one specimen". No attempt was made to apply rules of parsimony to reduce "number of 'specimens'" to "numbers of 'individuals'".

SITE DESCRIPTIONS

1. BUGDENS SUPERMARKET, DRAYTON

Exposure

During June/July 1990, excavations for the foundations of a new supermarket for the Bugdens chain of stores exposed a minor section in the lower *mucronata* zone. The section, located on the main road between Drayton and Taverham (TG 177 137; Fig.1) presented a sloping face 1.5 - 2.0m high where it was cut into the side of a hill. Excavated material was dumped on site where it could be examined. This consisted of large (0.5 - 1.0m) blocks of chalk.

Lithology

The chalk was soft, poorly consolidated and in places somewhat fissile owing to the presence of frequent, closely-spaced (2 - 5 cm), omission surfaces. A thin (3mm) band of flaser chalk was recognised in one of the blocks. The chalk was white except where stained yellow by downwash from the overlying unfossiliferous Quaternary sands and gravels. The chalk was very weakly cemented and could be disaggregated by simple immersion in water for five minutes, and thereafter hosed through a sieve.

No flint bands were seen *in situ*, however, there were two types present in the chalk blocks. The first were slender burrow-flints which were very strongly developed below at least one omission surface, where their tightly interdigitating extensions contributed an estimated 60+% by volume of the rock. These were very sharply confined to a layer 5-10 cm thick below their associated omission surface. The cross sections of the burrow flints

were often conspicuously flattened. Some siliceous straw-like fragments recovered from sediment samples were apparently imperfectly flint-filled thalassinid burrows.

The second type were large, robust, "horned" flints, i.e. overgrown thalassinid flints, some of which were packed with *Echinocorys*. A large flint ammonite was found with a sandy, iron-stained and leached upper side and chalky underside. This clearly came from the junction of the chalk with the overlying sands and gravels. Since these are usually, if not always found at the level of major flint bands it is inferred that the robust flints probably formed the upper of two courses, the lower being occupied by the gracile thalassinid flints mentioned previously.

Some of the chalk had clearly been cryoturbated: a few blocks contained trails of brown sandy loam surrounding chalk clasts embedded in a lime mud. There were also some apparent shear planes seen in some of the larger blocks of chalk, perhaps indicating incipient, minor, glacially induced rafting in the vicinity.

Stratigraphy

Inspection of Woods' 1988 map of the sub-zones of the Norwich chalk (based in part on Peake & Hancock, 1961; 1970) shows that the section should be in chalk of the Pre-Weybourne-2 sub-division of the *mucronata* zone, which is characterised by abundant colonies of the cheilostome bryozoan *Volviflustrellaria taverensis* (Brydone). That species was abundant in samples confirming the expected stratigraphical position (see Appendix 1). The few belemnites recovered lacked the alveolar cavity, but were all robust forms, perhaps referable to *Belemnitella ex groupa senior*. The large flint pachydiscid ammonite had numerous moulds of the irregular echinoid *Galeola* stuck to its surface; these are also characteristic of this horizon, though the genus ranges at least as high as the base of the Weybourne Chalk, where it may be very common (Whittlesea, unpublished data).

NEW FAUNAL RECORDS FROM DRAYTON

Bryozoa

Colonies of the distinctive bryozoan *Bicavea striata* Gaster were recovered in some abundance. Gaster (1932) recorded this species from the *Actinocamax quadratus* zone of Hampshire; this is the first record from Norfolk and from a somewhat younger horizon.

Apart from *Volviflustrellaria taverensis* (Brydone), there are at least five other species of lunulitid bryozoa present at this horizon (including species of *Pavolunulites*) making it one of the richest for this group in the *mucronata* chalk. *V. taverensis* persists into the middle Weybourne Chalk, but with a fan-shaped zoarium in marked contrast to the well-known spindle-shaped zoaria that have been extensively figured by several authors (Whittlesea, unpublished data). The lunulitiform arachnopusiid *Stichocados verruculosus* Marsson was also common.

Incertae sedis

Several specimens of the putative bryozoan *Porina scoriacea* Brydone were recovered; Brydone (1930) described the species originally from the *mucronata* zone of Meudon, France. The author has also recorded it from the middle Weybourne Chalk of Eaton chalk pit (TG 208 603) - the highest horizon yet, where it is very scarce. Examination of Brydone's type and the new material casts considerable doubt on the bryozoan affinities of this taxon; it certainly is not an ascophoran. It might possibly belong in the aberrant anascan bryozoan family Skyloniidae Sandberg 1963.

2. WHITLINGHAM SEWAGE WORKS

Exposure

The Anglian Water Authority contracted Biwaters Limited to extend their sewage treatment plant at Whitlingham (TG 278 077; Fig.1) during the Spring and Summer of 1990. The extensions were made necessary by the growth in the population of the city of Norwich in the twenty years since the plant was installed.

The original excavations in the 1970s had exposed some strata of Maastrichtian age (P. Cambridge and N. Peake, pers. comm.) in what is believed to be the eastern end of a huge glacial erratic extending from a location near Crown Point (TG 248 073). This erratic overlays strata of Paramoudra Chalk age (Peake & Hancock 1961, 1970). Wood (1988, pp. 95-95) stated that the chalk surface was overlain by Norwich Crag and that Till could be seen to undercut the chalk at one end of the section. The fauna collected included *Echinocorys* con-specific with material collectable from about band 'S' of the *Porosphaera* Beds on the north Norfolk coast (material now in the P. G. Cambridge collection, housed in the Sedgwick Museum, University of Cambridge). Specimens exhibited all of the

features of the Sidestrand material, viz. blotchy grey coloration of the test owing to incipient silicification, and an identical epifauna. It also yielded thalassinid burrow flints in chalk containing *Echinocorys* comparable with those of the *Pyramidata* hardground on the north Norfolk coast (Wood, 1988, p. 94). (The *Pyramidata* hardground has been proposed as marking the Campanian - Maastrichtian boundary in Norfolk.) It was hoped that the new excavations would re-expose the same strata, and the erratic in particular, in order to enable further observations to be made.

The main excavation for the settling tanks was nearing completion when visited. Owing to the water-logged nature of the chalk the section did not present a clean face making it difficult to produce an accurate log. However, a couple of substantial tabulate flint bands were present, spaced about one metre apart, and a very few large Paramoudras were found on the spoil heaps, though none were seen *in situ*. The aggregate thickness of chalk exposed in the walls of the settling tanks and in deeper excavations in the floor of the site was approximately 10 metres.

Lithology

The chalk at Whitlingham is exceedingly soft: sediment samples could be disaggregated simply by immersion in water for 10 to 15 minutes, at the end of which they acquired the consistency of a stiff porridge. Once in this state the material could be hosed through a sieve to produce a residue from which the fossils could be picked out. This facilitated processing a much larger sample than would normally be attempted. Some 50kg were processed yielding a diverse fauna in excess of 150 species (Appendix 2).

This lithology is substantially different from that of the famous Thorpe "cast" bed and the overlying Postwick hardground complex (TG 286 080). The Thorpe "cast" bed is a major orange-yellow chalk hardground complex sandwiched between firm white chalk, and was formerly exposed in a pit at Thorpe-next-Norwich (TG 276 090) now a Sainsbury's Superstore. It was a source of surprise that there were no hard bands at all in the excavation which had an aggregate depth in excess of 10 metres. This lithology is superficially like that of part of the lower *mucronata* zone (cf. Drayton).

Stratigraphy

The high Paramoudra Chalk is poorly exposed in Norfolk. Inland there are very few sections and no unequivocal stratigraphical overlaps have been demonstrated between these. Several of the critical sections (probably the majority) are glacial erratics making the construction of a detailed lithostratigraphy problematic. In the absence of a standard succession, these erratics would be unusable were it not for the fact that the strike of the Chalk is almost due north-south over much of the county, and the direction of movement of the glaciers that emplaced them is believed to have broadly coincided with it. The result is that an individual erratic should preserve its correct stratigraphical relationship with its neighbours irrespective (within limits), of distance moved.

Wood (1988, pp. 37-39) split the Paramoudra Chalk into Paramoudra-1 and Paramoudra-2 on the basis of lithology and palaeontology. (Wood mentioned several taxonomic groups, but only the echinoids will be commented on below.) Paramoudra-1 was defined as being characterised by abundant columns of paramoudras and to be highly fossiliferous, with sporadic *Micraster ciplyensis* Schlueter and *Echinocorys ex. gr. belgica* Lambert. Whitlingham (TG 2687 0766), was given as the only extant inland reference section. Wood (1988) also commented on the fact that the coastal sections were not nearly as rich in macro-fossils as their presumed inland equivalents.

Paramoudra-2 was defined as being composed predominantly of yellow, richly fossiliferous chalk with beds of moderately indurated chalk developed at several horizons. Huge, overgrown thalassinid nodular flints rather than paramoudras are characteristic, though the latter are reported. The horizon is characterised by common *Micraster ciplyensis*. Postwick Grove (TG 287 080) was given as a reference site, along with Thorpe St. Andrews pit and Thorpe Tollgate pit, though only Postwick Grove is extant. Wood (1988) thought that Postwick Grove was *in situ*, a point commented upon below.

The lithology, thickness and palaeontology of the chalk seen in the temporary section at Whitlingham does not fit either of these definitions, even if the data included in individual site logs is taken into account along with the broader, formal definitions used. Lithologically, the site presents a ~10m thick sequence of pure white, weakly cemented chalk, deposited as units 0.7-1.0m thick; indurated layers are apparently absent. Flints are massive tabulates with very scarce, huge paramoudras with a very narrow chalk core. The chalk is very sparsely fossiliferous, intact macro-fossils are rare, and the washing residue is

minuscule. Test fragments recovered from washing residues indicate that *Cardiaster* and *Echinocorys* were the most abundant echinoderms, followed by infrequent *Hagenowia*, and that *Micraster* was exceedingly scarce. The flint bands in the 100m square, 4m deep excavation were straight and level around three sides of the excavation, giving no cause to suspect any transportation.

In order to integrate Whitlingham into the Paramoudra Chalk stratigraphy it is necessary to review the relationships of all the recent exposures at this horizon.

Recent Temporary Sections in the Yare valley

1. In 1992, construction of the bridge supports that took the Norwich Southern Bypass across the Yare valley (TG 2745 0780) encountered chalk on the southern bank of closely similar facies to that seen in the Whitlingham temporary section. A small sample was collected, and yielded the fauna given in Appendix 3. It has clear affinities with that collected from the sewage works extension site.

2. In March/April 1993, maintenance work on a pipeline (TG 2810 0870) carried out by British Gas encountered the famous Thorpe "cast" bed (actually, a major hardground sequence), and produced steeply conical *Micraster ciplyensis*, belemnites, and some important new bryozoan taxa (Appendix 4). The chalk was firm and yellow with occasional harder lumps that contained moulds of sponges and molluscan invertebrates; the spoil heaps yielded large thalassinid flints.

3. In June/July/August 1993, work undertaken to lay a 0.75m diameter pipe from Brundall to convey sewage to the original sewage treatment plant at Whitlingham. The course of the pipeline took it south across the river just east of the bridge carrying the Southern Bypass. It encountered soft white chalk in deep excavations on the north river bank (TG 2825 0820), and firm yellow chalk at depth where the pipeline went underneath the Norwich - Sheringham branch railway line 800m further ENE (TG 2900 0825). (Note that where the pipeline went under the railway line it was about 10m higher than where it crossed the river bank.) Samples were taken from each location, and yielded the faunas given in Appendices 5 and 6. The course of the pipeline in its final approach across marshland to the sewage works took it south-west immediately behind the original sewage

works. The pipeline was not laid very deeply so the trench threw up little chalk. However, material that was exposed was the same facies as seen in the sewage works extension site. No samples were taken. No trace was seen of the Maastrichtian erratic mentioned earlier.

4. In July/August 1993, work to construct a roundabout at the junction of the access road to St. Andrew's Business Park (Central Avenue) and the Yarmouth Road (TG 2795 0875) exposed a 2.0 - 1.7m high, 50m long section in the Chalk. The chalk surface, which showed no signs of disturbance, was overlain by shelly sands of the Norwich Crag Formation. The section showed white, yellow/orange mottled, phosphatic chalk with lenses of fawn-coloured friable arenaceous chalk and three thalassinid burrow flint bands. The section yielded the fauna given in Appendix 7. Clearly, this is the same fauna as [2] above, although the section was about 1.5m higher (since the base of this section was just above road level). During later stages of construction, a large erratic of very soft white chalk was visible high above intensely disturbed Norwich Crag and Till at the easternmost end of the section.

The height above O.D. of the chalk surface seen in [4] above could be determined accurately because it was adjacent to a 25' (7.62m) surface level shown on the 1965 1:10,000 O.S. map for square TG 28 08. In Norfolk the regional dip of the Chalk surface is 1.52m per km east, with a slight north-easterly component. and the formational dip of the Chalk is 6.66m per km (Boswell, 1920). Using this data, a value for the height of the Chalk surface at Postwick Grove, taken from the 1993 1:25,000 O.S. map for square TG 20/30, was cross-checked against the calculated value [4 above] and proved to be in close agreement.

The top of the Whitlingham sewage works extension section was below the 5m contour and had a total aggregate depth of 10m. The chalk surface was not seen. It exposed only soft white chalk. The top of the extant Postwick Grove section is at or about the 8m contour. Currently, it is about 2m high, but a temporary excavation into the talus at the base of the section has proved a total of at least 6.2m. The section exposes a rhythmic sequence of chalk facies in mostly firm yellow chalk that includes several hardgrounds. Slickensiding is conspicuous on some of the vertical chalk joints suggesting that the site may have been subject to minor glacial disturbance. A river beach section downstream of

the Grove, which is exposed intermittently at low tide, reveals disturbed white chalk (Wood, 1988, p.99; Whittlesea, unpublished observations) overlain by yellow chalk.

Postwick Grove is 0.6km east of Whitlingham and the bottom of the 6m section with its firm yellow chalk facies extends down at least as far as 2.0m O.D. Were the top of Whitlingham as high as 5m O.D. then 0.6km further east at Postwick Grove this horizon would be at 1m O.D. This calculation indicates an underlap between the two sites of 1m. which is supported by field observations. It appears that Whitlingham could fit stratigraphically beneath Postwick Grove and that the soft white chalk seen on the river beach would then be equivalent to a horizon slightly above the section at Whitlingham.

The failure to find any additional highest Campanian/low Maastrichtian fossils or facies is explicable when the erratic nature of the 1970s sewage farm excavation is taken into account, along with the fact that it was several hundred metres to the north-west of the sewage works extension site and some 10m higher. Moreover, the Whitlingham sewage works extension section would be separated from the *Pyramidata* horizon by at least the 6m revealed in the Postwick Grove section in addition to whatever thickness separated the top of that section from the *Pyramidata* horizon.

The presence of younger *ex situ* Maastrichtian/*Pyramidata* chalk overlying older *in situ* Campanian chalk indicates westward movement of an erratic less than 0.5km from a former site at Whitlingham to the west of the ruins of St. Andrew's church (TG 2734 0786) which exhibited a tight anticlinal structure in Campanian chalk (Taylor, 1865; Woodward, 1876) indicating eastward movement. This stresses the need for caution in evaluating exposures in a region where the erratic nature of any chalk exposed is not always readily apparent in minor excavations.

On the coast, the chalk exposed in the Whitlingham sewage works extension would correspond to part of the 2km present between East Runton and Cromer. The very soft lithology would account for the absence either of derived fossils from this horizon, or of records of glacial erratics composed of this material in this interval.

Whitlingham: youngest unit of Paramoudra-1

The Whitlingham sewage works extension exposed the youngest unit of the Paramoudra-1 Chalk recognised to date. It consists of ~10m of soft, white, weakly cemented chalk, apparently entirely lacking in indurated horizons, deposited in units 0.7 - 1.0m thick, with

Table 2. Broad correlation between coastal and inland exposures with an indication of the characteristic lithology exhibited in the Paramoudra Chalks

Age/Lithology	Coast	Inland	Thickness (m)
MAASTRICHTIAN			
Porosphaera Beds	Sidestrand	Bramerton Common Wroxham boreholes	
Pre-*Porosphaera* Beds	Overstrand GAP	Not recognised unequivocally GAP	
CAMPANIAN/MAASTRICHTIAN BOUNDARY			
Pyramidata hardground	Overstrand	Whitlingham sewage farm (original)	
Soft white chalk		Bramerton "Woods End" P.H. (west end)	
	GAP	GAP	
CAMPANIAN			
Paramoudra-2			
Predominantly yellow chalk, massive thalassinid flints, frequent "metamoudras" and paramoudras			
		Postwick Grove	6.0-8.0
	Cromer Lighthouse (derived fossils)	Pound Lane/Thorpe Tollgate Whitlingham (St. Andrews Church)	2.0+
	Cromer pier to East Runton (only occasionally exposed)	Not recognised unequivocally	4.0+
Paramoudra-1			
Soft white chalk, massive tabulate flint bands, very occasional large paramoudras			
	East Runton	Whitlingham sewage works (extension)	10.0
Predominantly white chalk with common paramoudras			
	East Runton	Horstead (section no longer exists)	6.0+
Paramoudra-1/Beeston			
	West Runton	St. James' Hollow	6.0+

thick, tabulate flints bands below approximately every third or fourth major omission surface; massive paramoudras are present, albeit very scarce, with a narrow, cylindrical chalk core. The echinoid fauna as deduced from washing residues is characterised by *Cardiaster* and *Echinocorys*, with infrequent *Hagenowia*. *Micraster* is exceedingly scarce. The relative scarcity of paramoudras and the minuscule yield from washing residues contrasts sharply with that recorded for older horizons exposed inland in the Paramoudra-1 Chalk.

Table 2 gives an indication of the relationships between the key sections mentioned. Thicknesses are shown for the Paramoudra Chalk only, these are estimates and do not allow for any overlaps that may be present.

NEW FAUNAL RECORDS FROM WHITLINGHAM

Echinoids

Slender rostra of the irregular echinoid *Hagenowia elongata* (Nielsen, 1942) were found in several samples. Specimens of this genus are not well represented in museum collections, though it occurs regularly in sediment samples throughout much of the upper Upper Campanian of Norfolk (Whittlesea, unpublished data), and may be the commonest irregular echinoid at some horizons (e.g. in part of the middle Weybourne Chalk).

Comatulids

A centrodorsal of *Hertha plana* Nielsen was recovered; this is only the second specimen of this species to be found in Britain (A. B. Smith, pers. comm.). Comatulid centrodorsals are very rare: this specimen is the only one that the author has found in 17 years collecting. A specimen of *Dioptropora brevis* Marsson was recovered.

Bryozoa

This is the first record for the British chalk. Several specimens of *Tricephalopora vermicularis* (von Hagenow) were recovered. Whittlesea (1990) proposed that it might be a useful complementary guide fossil for the Maastrictian. Clearly, this is no longer the case.

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REFERENCES

BOSWELL, P. G. H. 1920. On the surface and dip of the Chalk in Norfolk. *Transactions of the Norfolk and Norwich Naturalists' Society*, **11**, 22-58.

BRYDONE, R. M.. 1930. Further Notes on New or Imperfectly Known Chalk Polyzoa. London, Dulau & Co.

CHRISTENSEN, W. K. 1975. Upper Cretaceous belemnites from the Kristianstad area in Scania. *Fossils and Strata*, **7**, 1-69.

CHRISTENSEN, W. K. 1995. *Belemnitella* from the Upper Campanian and Lower Maastrichtian Chalk of Norfolk, England. Special Papers in Palaeontology, **51**, 1-84

GASTER, C. T. A. 1932. The zones of the Chalk of the Arun Gap, Sussex: with a description of new species of *Bicavea*. *Proceedings of the Geologists' Association*, **18**, 212-223.

PEAK, N. B. and HANCOCK, J. M. 1970. The Upper Cretaceous of Norfolk [reprinted with addenda and corrigenda]. *In* Larwood, G. P. and Funnell, B. M. (Eds.) The Geology of Norfolk.

TAYLOR, J. E. 1865. On a displacement of the Chalk at Whitlingham. *Geological Magazine*, **2**, 324.

WOOD, C. J. 1988. The stratigraphy of the Chalk of Norwich. *Bulletin of the Geological Society of Norfolk*, **38**, 3-120.

WOODWARD, H. B. 1876. The Geology of England and Wales. London.

WHITTLESEA, P. S. 1996. The palaeoecology of two chalks in the Upper Campanian of Norfolk, England. *Bulletin of the Geological Society of Norfolk*, **43**, 25-44.

Appendix 1:Drayton Fossil Inventory
(Figures to the right of each entry are the number of specimens).

Porifera

Porosphaera globularis (Phillips)	74
Porosphaera sessilis Brydone	33
Porosphaera patelliformis Hinde	2
Porosphaera sp. juv.	65

Anthozoa

Moltkia spp., (A & B)	16
Stephanophyllia clathrata (von Hagenow)	2
Coelosmilia spp.	16

Brachiopoda

Isocrania costata (Sowerby, J. de C.)	10
Isocrania sp.	23
Cretirhynchia sp.	15
Terebratulina chrysalis (Schlotheim)	2
Terebratulina gracilis (Schlotheim)	3
Terebratulina rigida (Sowerby, J.)	10
Terebratulina spp. indet.	16
Argyrotheca hirundo (von Hagenow)	1
Argyrotheca sp. cf. *bronni* (von Hagenow)	1
Rugia tenuicostata Steinich	7
Rugia spinicostata Johansen & Surlyk	4
Aemula inusitata Steinich	1
Kingena pentangulata (Woodward)	1
Leptothyrellopsis polonicus Bitner & Pisera	6
Magas sp.	3

Bivalvia

Pseudoptera coerulescens (Nilsson)	1
Mimachlamys cretosa Defrance	1
Lyropecten (*Aequipecten*) *sarumensis* (Woods)	1
Spondylus dutempleanus d'Orbigny	1
Plicatula hantoniensis Brydone	6
Atreta nilsson (von Hagenow)	12
Plagiostoma sp.	1
Pseudolimea granulata (Nielsen)	2
Pycnodonte vesiculare (Lamarck)	2
Gryphaeostrea canaliculata (J. Sowerby)	10
Acutostrea cf. *incurva* Nilsson	1
Gyropleura inaequirostrata (S. Woodward)	2

Cephalopoda

Belemnitella sp.	3
Pachydiscus sp. (flint preserved ammonite.)	1

Crinoidea

Bourgueticrinus sp.	39
Nielsenicrinus sp.	1

Asteroidea

?*Arthraster* sp.	11
Crateraster sp.	2
Metopaster spp.	16
Nymphaster sp.	6
Pycinaster sp.	1
Recurvaster sp.	3
Goniasterid ossicles (spp. indet.)	162

Ophiuroidea

Ophiomusium sp.	12
Ophiuroid	1

Echinoidea

Temnocidaris (*Stereocidaris*) *serrata* (Desor)	150
Salenia sp.	1
Phymosoma sp.	1
Echinocorys subconicula Brydone	12
Galeola sp.	3

Cirripedia

Eoverruca sp.?	1
Arco-/Creti-scalpellid	3

Bryozoa, (Cyclostomata)

Stomatopora pedicellata Marsson	1
Stomatopora sp.	1
Diastopora spp. (2 species)	4
Clausa globulosa d'Orbigny	72
Crisisina unipora (d'Orbigny)	1
Disporella irregularis d'Orbigny	8

Pustulopora spp. (4 species)	130
Spiropora verticillata Goldfuss	1
Bicavea striata Gaster	27
Osculipora truncata (Goldfuss)	4
Trochiliopora sp.	14
Meliceritites sp.	54
Meliceritella sp.	3
Sulcocava sp.	8
Clypeina rosula von Hagenow	9
Eohornera langethalii (von Hagenow)	1
Nevianopora sp.	1
Petalopora / Sparsicava sp.	50
Idmonea sp.?	1
Aggregopora catenosa Voigt	1
Bryozoa, (Anasca)	
"Micropora" bedensis Brydone	1
Ellisina simplex (d'Orbigny)	1
Biflustra flabelliformis d'Orbigny	195
Biflustra argus d'Orbigny	13
Biflustra sp.	1
Aplousina cf. fulgora (Brydone)	1
"Membranipora" exhauriens Brydone	1
"Membranipora" tenebrosa Brydone	1
"Membranipora" withersi Brydone	1
"Membranipora" ex groupa sevingtonensis Brydone	1
Quadricellaria grania (Brydone)	2
"?Hiantopora" sp.1 *pavolumulitiform*	57
"?Hiantopora" sp. 2 *vinculariform*	18
Callopora lyra (von Hagenow)	1
Callopora sp.	1
Dionella trigonopora (Brydone)	1
Bryozoa, (Coilostega)	
Volviflustrellaria taverensis (Brydone)	26
Lumulites spp.(4 species)	4
Lumulites tenax Brydone	18
Lumulites? sp. nov.?	15
Pavolumulites spp.(2 species)	15
Omoiosia lepida (von Hagenow)	1
Onychocella allas (Brydone)	3
Onychocella congesta (Marsson)	1
Onychocella gibbosa Marsson	15
Onychocella inelegans (Lonsdale)	32
Onychocella cf. matrona (von Hagenow)	1
Onychocella norfolcia Brydone	24
Onychocella strumulosa (Marsson)	35
Onychocella spp.	
Virgocella virgo (von Hagenow)	3
Latereschara galeata von Hagenow	30
Latereschara cf. hantonensis Brydone	1
Coscinopleura sp.	9
Escharifora sp.	1
Micropora biforis (Marsson)	1
Micropora aff. monticula Brydone	2
Puncturiella sp.	1
Bryozoa, (Cribrimorpha)	
Andriopora sp.	1
Ubaghsia crassa (Lang)	16
Stichocados verruculosus Marsson	15
Leptocheilopora sp.?	1
Pancheilopora sp.?	1
Tricephaloporella keswickensis Whittlesea MS	8
Pliophloea spp.	5
Keratostoma sp. nov.	1
Tricephalopora sp.	7
Bryozoa, (Ascophora)	
Cryptostoma sp.	1
Beisselina sp.	8
"Porina" scoriacea Brydone	4
Porina sp.	1
Serpulida	
Glomerula gordialis (Schlotheim)	233
Neomicrorbis crenatostriatus (Munster)	28
Filogranula cincta (Goldfuss)	34
Sclerostyla macropus (Sowerby)	15
Ditrupula contracta (Sowerby)	3
Vermiliopsis sp.	12
Pisces	
Cretolamna spp. (2 species)	2
Pseudocorax sp.	1
Fish teeth, (2 species)	5
Fish scales	10
Fish vertebrae	13
Fish (indet. components)	4

Appendix 2: Whitlingham Fossil Inventory

(Figures given to the right of entries are the number of specimens).

Porifera

Porosphaera globularis (Phillips) 24
Porosphaera sessilis Brydone 25

Anthozoa

Moltkia spp. (A & B) 13
Stephanophyllia clathrata (von Hagenow) 12

Brachiopoda

Ancistrocrania parisiensis (Defrance) 1
Isocrania costata (Sowerby, J. de C.) 24
Cretirhynchia limbata (Schlotheim) 9
Carneithyris subcardinalis (Sahni) 11
Terebratulina chrysalis (Schlotheim) 5
Terebratulina faujasii (Roemer) 11
Terebratulina spp. indet. 6
Argyrotheca bronnii (Roemer) 1
Argyrotheca hirundo (von Hagenow) 1
Argyrotheca cf. coniuncta Steinich 1
Rugia tenuicostata Steinich 1
Aemula inusitata Steinich 2
Kingena pentangulata (Woodward) 1
Leptothyrellopsis polonicus Bitner & *Pisera* 3
Magas chitoniformis (Schlotheim) 1

Bivalvia

Pseudoptera coerulescens (Nilsson) 2
Mimachlamys denticulata (von Hagenow) 1
Merkelina sp. 3
Lyropecten (*Aequipecten*) *sarumensis* (Woods) 3
Neithea sexcostata (S. Woodward) 13
Spondylus dutempleamus d'Orbigny 8
Plicatula hantonensis Brydone 1
Atreta nilssoni (von Hagenow) 1
Plagiostoma sp. *cf. marrotiana* d'Orbigny 1
Plagiostoma cretaceum Woods 1
Pseudolimea granulata (Nilsson) 16
Inoceramus sp. 31
Pycnodonte vesiculare (Lamarck) 20
Gyrphaeostrea canaliculata (J. Sowerby) 1
Agerostrea ungulata (Schlotheim) 4
Gyropleura inaequirostrata (S. Woodward) 4

Cephalopoda

Belemnitella cf. langei Jeletzky 20
Ammonite granulaptychus (Baculites?) 1

Crinoidea

Austinocrinus sp. 2
Nielsenicrinus agassizi (von Hagenow) 7
Bourgueticrinus sp. *cf. constrictus* (Hagenow) 6
Bourgueticrinus sp. *cf. granulosus* Peron 1
Bourgueticrinus spp. indet. 23

Asteroidea

?*Arthraster* sp 1
Crateraster sp. 54
?*Crateraster* sp. 13
Goniasterid ossicles (spp. indet.) 16

Ophiuriodea

Ophiomusium subcylindricum (von Hagenow) 6

Comatulida

Hertha plana von Nielsen 1

Echinoidea

Cidaris spp. 21
Phymosoma sp. 3
Centrostephanus fragilis (Wiltshire) 3

Echinocorys sp.) 292
Cardiaster sp.)

Only large test fragments of Echinocorys and Cardiaster can be discriminated confidently, so samples for these two genera are bracketed together.

Micraster sp. 2
Hagenowia elongata (Nielsen) 5

Cirripedia

Scalpellum (*Arcoscalpellum*) *maximum* (J. de C. Sowerby)	5
Brachylepas fallax (Darwin)	2
Verruca prisca Bosquet	1
indet. scalpellid	1

Bryozoa, (Cyclostomata)

Stomatopora sp.	5
Stomatoporopsis sp.	1
Proboscina sp.	1
Diastopora sp.	10
Pustulopora spp. (3 species)	29
Petalopora marssoni (Gregory)	31
Petalopora sp. #2	2
Clypeina rosula von Hagenow	2
Nevianopora sp.	1
Theonoa sp.	5
Defranciopora sp.	3
Homaeosolen sp.	10
Fasciculipora sp.	1
Osculipora sp.	1
Eohornera langethalii (von Hagenow)	11
Clinopora sp.	6
Retecava sp.	4
Meliceritites cf. gothica Levinsen	54
Disporella irregularis d'Orbigny	1
Sulcocava lineata Marsson	1
Crisisina carinata (Romer)	6
Marssoniella sp.	3
Tervia sp.	5

Bryozoa, (Anasca)

"Biflustra" argus d'Orbigny	64
Callopora invigilata (Brydone)	4
Dionella surculus (Brydone)	1
Dionella trifaria (von Hagenow)	2
Dionella trigonopora (von Hagenow)	7
Dionella aff. triminghamensis (Brydone)	1
Ellisina britannica (Brydone)	1
Ellisina ringens (von Hagenow)	1
Elisina simplex (d'Orbigny)	1
"Membranipora" hegamone (Brydone)	14
"Membranipora" withersi Brydone	1
Quadricellaria grania (Brydone)	2
"Membranipora" cf. galvia Brydone	1
Semieschara labiatula Brydone	2

Bryozoa, (Coilostega)

Floridina canui (Brydone)	2
Lunulites cretacea Defrance	20
Lunulites beisseli Marsson	2
Homalostega aff. cuneiformis Brydone	1
Homalostega nitescens Brydone	1
Homalostega punctilla Reuss	1
Onychocella gibbosa (Marsson)	13
Onychocella hercyna Brydone	1
Onychocella inelegans Lonsdale var. incarcerata Brydone	24
Onychocella irregularis von Hagenow	3
Onychocella matrona von Hagenow	18
Onychocella norfolcia Brydone	24
Onychocella piriformis (Goldfuss)	1
Onychocella rowei/mimosa Brydone	38
Coscinopleura lamourouxi von Hagenow	2
Woodipora disparilis (d'Orbigny)	44

Bryozoa, (Cribrimorpha)

Thoracopora sp. nov.(?) #1	1
Thoracopora sp. nov.(?) #2.	2
Pancheilopora sp. nov.(?)	1
Pliophloea sp.	4
Polycephalopora sp. nov.(?)	2
Castanopora spp. nov.(?)	4
Phractoporella constrata Lang	14
Phractoporella cf. operta Lang	1
Tricephalopora obducta (Lang)	4
Tricephalopora vermicularis (von Hagenow)	1
Hesperoporella cf. aviculosa Whitttlesea MS	1
Ubaghsia reticulata (Ubaghs)	2
Keratostoma niemeyeri Voigt	1
Stichocados verruculosus Marsson	1

Bryozoa, (Ascophora)

Cryptostoma corallinum Brydone	1
Cryptostoma globedecus Brydone	1
Cryptostoma lagenale Brydone	1
Porina disticha (Goldfuss)	11
Porina pachyderma Marsson	1

Beisselinopsis sp. nov.(?)	1
"Dioptropora" brevis Marsson	1
"Porinid" spp. (6 species)	6
Systenostoma asperulum Marsson	11
Serpulida	
Glomerula gordialis (Schlotheim)	44
Neomicrorbis crenatostriatus (Munster)	26
Neomicrorbis subrugosus (Munster)	2
Tetraserpula canteriata (von Hagenow)	3
Proliserpula ampullacea (Sowerby)	3
Filogranula cincta (Goldfuss)	8
Vermiliopsis dorsolineata (Nielsen)	1
Vepreculina fimbriata Regenhardt	3
Vepreculina tuberculifera (Nielsen)	4
Eoplacostegus pusillus (Sowerby)	1
Cementula sp.	1
Pisces	
Scapanorhynchus rhaphiodon (Agassiz)	1
Synechodus recurvus (Trautschold)	1
Fish vertebrae, teeth and scales	7

Appendix 3: Fossil Inventory

Norwich Southern Bypass bridge foundations (southern bank), Whitlingham Lane, TG 275 078. The whole section was topographically above that present in the sewage works excavation.

Slightly firmer chalk than that in the sewage works excavation, with omission surfaces much more closely spaced, many fossils tending to have a pinkish coloration.

Porosphaera globularis (Phillips), *P. sessilis* Brydone; *Stephanophyllia clathrata* (von Hagenow), *Moltkia* sp.; *Cretirhynchia* sp., *Terebratulina* sp.; *Pseudoptera coerulescens* (Nilsson), *Neithea sexcostata* (Woodward); *Nielsenicrinus agassizii* (von Hagenow), *Bourgueticrinus* sp.; *Metopaster* sp.; *Ophiotitanos* sp., *Ophiomusium* sp.; *Stereocidaris* sp., *Phymosoma* sp., *Centrostephanus* sp., *Galerites* sp., *Cardiaster* sp., *Echinocorys* sp., *Hagenowia* sp.; *Ditrupula contracta* (Sowerby), *Glomerula gordialis* (Schlotheim), *Eoplacostegus pusillus* (Sowerby), *Neomicrorbis crenatostriatus* (Munster); *Verruca prisca* Bosquet, *Scalpellum sp.*, *Proverruca* sp.; *Disporella irregularis* (d'Orbigny), *Crisisina carinata* (Roemer), *Eohornera langethalii* (von Hagenow), *Petalopora marssoni* Gregory, *Pustulopora* sp., *Clinopora* sp., ?*Ceriopora* sp.; *"Biflustra" argus* d'Orbigny, *"Membranipora" seafordensis* Brydone, *Callopora invigilata* Brydone, *Onychocella matrona* von Hagenow, *Onychocella rowei* Brydone, *Onychocella gibbosum* Marsson, *Onychocella strumulosa* (Marsson), *Lunulites* sp., *Rotiporina angustata* d'Orbigny, *Porina disticha* (Goldfuss), *Castanopora magnifica* (d'Orbigny), *Tricephalopora* sp. nov., *Beisselina* sp.

Appendix 4: Fossil Inventory

British Gas pipeline excavation (Yarmouth Road, A47) c.TG 281 087
Hardground complex including part of the Thorpe "cast" bed.

Porosphaera globularis (Phillips); *Isocrania costata* (Sowerby), *Carneithyris subcardinalis* Sahni, *Argyrotheca* sp., *Terebratulina* sp.; *Lyropecten* (*Aequipecten*) *campaniensis* (d'Orbigny), *Neithea sexcostata* (S. Woodward), *Gyropleura inequirostrata* (S. Woodward), ?*Hyotissa* sp.; *Nielsenicrinus* sp., *Bourgueticrinus* sp.; *Stereocidaris* sp., *Phymosoma* sp., *Centrostephanus* sp., *Galerites* sp., *Echinocorys* sp., *Micraster ciplyensis* Schlueter; *Glomerula gordialis* (Schlotheim), *Neomicrorbis crenatostriatus* (Munster), *Filogramula cincta* (Goldfuss), *Vepreculina* sp.; ?*Brachylepas* sp.; *Belemnitella langei* Jeletzky; *Diastopora* sp., *Disporella irregularis* (d'Orbigny), *Meliceritites* sp., *Meliceritella* sp., *Crisia* sp., *Tervia* sp., *Homaeosolen* sp., *Clausa franquana* d'Orbigny, *Petalopora marssoni* Gregory, *Defranciopora* sp., *Pustulopora* spp.; *"Biflustra" argus* d'Orbigny, "*Membranipora*" spp., *"Membranipora" furina* Brydone; *Onychocella inelegans* (Lonsdale), *Onychocella matrona* von Hagenow, *Onychocella rowei* Brydone, *Onychocella strumulosa* (Marsson), *Aechmella nonna* von Hagenow, *Lunulites cretacea* Defrance, *Coscinopleura lamourouxi* von Hagenow; *Porina goldfussi* Brydone, *Porina angustata* d'Orbigny, *"pseudo-Systenostoma"* sp.(undescribed genus of vincullariform *Hippothoidae*), *Beisselina nobilis* Levinsen, *"pseudo-Beisselina"* sp. (undescribed genus of erect, arborescent, bilaminate cribrimorph).

Appendix 5: Fossil Inventory

Anglian Water Authority sewage pipeline: deep excavation under river east of Southern Bypass bridge support on northern bank, TG 282 082.

Soft white chalk of same lithology as that encountered in the main sewage works excavation.

Coelosmilia spp. juv.; *Terebratulina* sp., *Argyrotheca* sp.; *Atreta nilssoni* von Hagenow, *Inoceramus* sp.; *Austinocrinus sp.*; *Stereocidaris* sp., *Cardiaster* sp., *Echinocorys* sp.; ?*Brachylepid barnacle*; *Stomatopora* spp. [two], *Berenicea* sp., *Pustulopora* sp., *Petalopora* sp., *"Biflustra" argus* d'Orbigny, *Onychocella inelegans* (Lonsdale), *Onychocella rowei* Brydone, *Omoiosia* sp., *Onychocella strumulosa* (Marsson), *Porina goldfussi* Brydone, ?*Systenostoma* spp.

Appendix 6: Fossil Inventory

Anglian Water Authority sewage pipeline: deep excavation under Norwich - Sheringham branch railway line in the vicinity of Whitlingham hospital, TG 290 082.

Winnowed yellow chalk and soft white chalk

Porosphaera globularis (Phillips); *Moltkia* sp., *Coelosmilia* sp.; *Ancistrocrania parisiensis* (d'Orbigny), *Isocrania costata* (Sowerby), *Cretirhynchia* sp., *Carneithyris* sp., *Magas chitoniformis* (Schlotheim), *Argyrotheca hirundo* (Hagenow), *Terebratulina faujasii* (Roemer), *Terebratulina chyrsalis* (Schlotheim), *Kingena* sp.; *Lyropecten* (*Aequipecten*) *campaniensis* (d'Orbigny), *Neithea sexcostata* (S. Woodward), *Plicatula hantonensis* Brydone, *Inoceramus* sp., *Gyropleura inequirostrata* (S. Woodward); *Austinocrinus bicoronatus* (von Hagenow), *Nielsenicrinus agassizii* (von Hagenow), *Bourgueticrinus* sp.; *Nymphaster* spp.; *Ophiomusium* sp.; "*Cidaris*" sp., *Centrostephanus* sp., *Echinocorys* sp.; *Ditrupula contracta* (Sowerby), *Glomerula gordialis* (Schlotheim), *Vermiliopsis fluctuata* (Sowerby), *Vermiliopsis* sp., *Filogranula cincta* (Goldfuss), *Neomicrorbis crenatostriatus* (Munster), *Neomicrorobis subrugosus* (Munster); Crustacean claw (same species as occurs at Eaton); ?*Aggregopora* sp., *Clinopora* sp., *Diastopora* sp., *Eohornera langethalii* (von Hagenow), *Homaeosolen* sp., *Idmidronea* sp., *Meliceritites* sp., *Pustulopora* sp., *Sulcocava* sp., *Siphoniotyphlus* sp., *Tervia* sp., "*Biflustra*" *argus* d'Orbigny, *Membranipora sp., Coscinopleura lamourouxi* von Hagenow, *Onychocella strumulosa* (Marsson), *Onychocella matrona* von Hagenow, *O. gibbosa* Marsson, *O. rowei* Brydone, *Lunulites* sp., *Puncturiella* sp., *Rotiporina* sp., *Porina pachyderma* Marsson.

Appendix 7: Fossil Inventory

St Andrew's Business Park roundabout (Yarmouth Road) TG 279 087.

Hardground complex including part of the Thorpe "cast" bed, (as Appendix 4) above but about 3m higher in the sequence and including 3-5cm long and 5mm thick chocolate brown lenticles of (?)phosphatic chalk.

Porosphaera sessilis (Phillips); *Carneithyris* sp., *Neoliothyrina* sp., *Cretirhynchia* sp.; *Mimachlamys cretosa* (Defrance), *Neithea* sp., *Gyropleura* sp., *Pycnodonte vesiculare* (Lamarck), *Belemnitella* sp.; ?*Parsimonia* sp., *Filogramula cincta* (Goldfuss), *Vepreculina tuberculifera* (Nielsen), *Sclerostyla macropus* (Sowerby), *Neomicrorbis subrugosus* (Munster); *Brachylepas* sp.; *Isselicrinus* sp. *cf. buchii* (Roemer); *Metopaster* spp.; "*Cidaris*" sp., *Phymosoma koenigi* (Mantell), *Centrostephanus* sp., *Echinocorys* sp., *Micraster ciplyenesis* Schlueter; *Stomatopora* sp., *Meliceritites* sp., *Herpetopora* sp., "*Membranipora*" *hexagona* (von Hagenow), "*Biflustra*" *argus* d'Orbigny, *Onychocella rowei/mimosa* Brydone, *Onychocella strumulosa* (Marsson), *Hoplitaechmella nitescens* Brydone, "*Rotiporina*" sp..

THE PALAEOECOLOGY OF TWO CHALKS IN THE UPPER CAMPANIAN OF NORFOLK, ENGLAND

Paul S. Whittlesea

8 Eaton Old Hall, Hurd Road

Norwich, NR4 7BE

ABSTRACT

A detailed palaeoecological interpretation of two temporary sites in the zone of ***Belemnitella mucronata*** *sensu lato (Upper Cretaceous, Upper Campanian) is presented. Comparison of the faunal composition of these sites indicates that environmental conditions were significantly different. Drayton is interpreted as a warm, shallow water environment, liable to frequent, low-volume sediment influxes that smothered large areas of the sea floor, preserving a succession communities. The dense, moderately diverse fauna was dominated by a suite of mostly small species belonging to a pioneer community. Whitlingham is interpreted as being a cooler, deeper water environment than Drayton, which was liable to regular (though not necessarily frequent), high volume sediment influxes that preserved a sparse, high diversity, mature community. No single phylum dominated the faunal community.*

INTRODUCTION

Whittlesea (1996) described temporary sections at Drayton and Whitlingham from which large and diverse faunas were recovered. Both sections were in the zone of *Belemnitella mucronata sensu lato*; Drayton is low down in the zone, and Whitlingham probably a few metres from the top. The sections were studied more than a year apart, and initial assessment of the lithology made whilst disaggregating samples from Whitlingham raised the expectation that they would afford some insight into rates of morphologic change in the boreal Late Cretaceous and, more speculatively, some of the factors affecting this.

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However, the palaeontological data contradicted this expectation: of the taxa that were recovered from the samples collected at Drayton, approximately 95% of the genera and 75% of the species survive into the Norfolk lower Maastrichtian (a younger horizon than that represented at Whitlingham), yet only 50% of species are common to both sites. These data demonstrated that there were more differences in the faunas than could be accounted for solely by the amount of morphologic change that had occurred during the 8m.y. that Cobban & Kennedy (1992) deduce the Upper Campanian to have lasted. The realisation that the Whitlingham palaeocommunity was not just a younger version of that at Drayton prompted the detailed reappraisal of the fauna - facies relationships reported here.

Full locality, stratigraphic details and data appendices for the sites discussed in this article are given in Whittlesea (1996).

TERMINOLOGY

In this paper, "dominant" taxa are defined as those with remains which contribute more than 5% of the total specimens found. "Abundant" taxa are those with remains that contribute more than 5% of the specimens belonging to their own phylum and at least 1% of the total specimens found (so as to eliminate scarce phyla). The selection of 5% and 1% is based on what (subjective) experience has demonstrated to be useful in previous research.

Primary encrusters can directly colonise physical niches (e.g. the sea floor).

Secondary encrusters encrust biogenic substrates and never occupy niches available to primary encrusters. Biogenic substrates may be living or dead (the latter may be fragmentary).

Pioneer communities are characterised by the presence of organisms capable of colonising freshly available physical environments essentially devoid of other macro-organisms and the virtual absence of members of mature communities.

Mature communities are characterised by the presence of organisms that cannot colonise an environment unless, or until, it has been colonised by members of pioneer communities.

This may be because they either need pioneering forms as substrates or hosts (either living or dead), or they need these forms to have modified the physical environment in some way to make it amenable to them (e.g. by dewatering or compacting the substrate).

SAMPLE YIELDS

A 3kg chalk sample, disaggregated and sieved through a 1 mm mesh (Whittlesea 1996) yields up to 200 specimens, where a specimen is a whole or substantial fragmentary skeletal component, identifiable at least to family level, and in practice, usually at least to generic level.

Larger samples (>1000 specimens) yield 90-110 species, of which the great majority, (49-57%) are bryozoa. No other phylum contributes more than 12% of the diversity, 2-10% being normal. A majority (39-54%) of the specimens will also be bryozoa. Echinoderm debris (all classes) is the next largest component, contributing 21-32% of material recovered, though the class level contributions vary enormously. Most other phyla contribute 0.5-5% each, though the contribution of some (e.g. serpulids and bivalves) may vary by an order of magnitude from facies to facies.

These observations are based on many years experience collecting and processing samples from the *mucronata* zone (chiefly the Weybourne and Beeston Chalks) and from the *lanceolata* zone (chiefly the *Porosphaera* Beds) in Norfolk.

SEDIMENTARY REGIMES

The original research motives for investigating these sites were palaeontological and stratigraphical rather than palaeoecological or sedimentological. On site no attempt was made to investigate the chalk for sedimentary structures, not least because of restricted access. Hence, any inferences drawn here about the sedimentary regimes under which the chalks were deposited are necessarily retrospective and indirect.

The chalk at Whitlingham is soft, structureless, and deposited in units 0.5-1.0m thick This yielded paramoudras, though only a few were seen on site. According to Bromley & Ekdale (1987, p.1088), these are diagnostic of allochthonous chalks.

The much smaller site at Drayton did not yield paramoudras thereby necessitating a more indirect approach to assessing the regime using palaeontological data. The fauna recovered from thin units between the closely spaced omission surfaces belonged to the

pioneer community. From this it is deduced that the length of time represented by the omission surfaces is brief because this community type initiates sea floor colonisation. Had the hiatuses been longer, members of more developed community types would be represented in samples. Therefore these communities were being exterminated by frequent sediment influxes before they could develop into anything more complex. Hence, both sites are inferred to have been excavated in allochthonous chalks.

PALAEOENVIRONMENTAL INTERPRETATION: DRAYTON

What is there to explain?

The chalk at Drayton displays very variably spaced omission surfaces, which tend to be clustered in sets of 5 - 10, spaced 1 - 2cm apart, followed by a similar number 10 - 30cm apart. The rock is weakly cemented, with a patchily developed ichnofauna: thalassinid burrow systems developed at some horizons, some preserved by flint infillings. Where the burrow systems are small the flints are gracile and sharply confined beneath their associated omission surface and typically have an oval rather than circular cross-section. Flints associated with larger systems may be massively overgrown. A synsedimentary marl band is developed beneath at least one horizon. Nodular chalks and hardgrounds are not developed, and there is no evidence of winnowed beds. Invertebrate fossils are well-preserved and show no signs of physical abrasion. Some echinoid tests show evidence of significant bioerosion, but other large, hard substrates (e.g. belemnite guards) are scarce. The fauna consists mainly of sessile benthos, is diverse, though dominated by a small number of taxa, and very dense.

Energy of the environment

Current action was never strong enough to develop winnowed beds, nodular chalks or hardgrounds; neither was it normally strong enough to exhume and or transport invertebrate remains, as shown by the frequent occurrence of anascan bryozoans with spines still articulated in place around their opesiae, and by the common occurrence of articulated asteroid arm fragments (a phenomenon rarely encountered routinely higher in the zone).

Substrate conditions

Though the chalk is very poorly cemented, the fauna is dominated by prodigious numbers of diminutive, sessile, epibenthonic, filter/suspension-feeding species, suggesting that there was no turbid suspension layer immediately above the substrate, which seems to have been firm and cohesive. The development of synsedimentary marl bands indicates a high organic content in the sediment resulting from a highly productive benthic community (Ernst, 1982).

The presence of a diverse, dense lunulitid bryozoan fauna (see further discussion below) enables inferences to be made about the depth and temperature of the environment. Modern species have a restricted distribution, preferring warm (habitually greater than 12°C), shallow (less than 200m) water, with low to moderate rates of deposition, but can tolerate fairly high velocity current regimes (Cook & Chimonides, 1983). They are rare or absent from regions with rocky areas of high turbulence, or subject to high silt deposition (Cook & Chimonides, 1983, Cadee, 1975).

Length of time represented by hiatuses

At two horizons, the hiatuses must have been long enough to enable sponge communities to establish themselves in order that their spicules could accumulate in sufficient numbers to make the flint bands. However, omission surfaces with flint bands developed beneath them are the exception here, and the fossil evidence (1-4 below) favours brief hiatuses.

1. With the exception of the asteroids, (and possibly some regular echinoids) other taxa belong to diminutive species, or failed to approach known maximal sizes.

2. Surlyk (1972) has attempted to ascertain probable life-spans of specimens of the abundant brachiopod *Terebratulina gracilis*, using a statistical analysis of growth lines. Results of this analysis suggest that this genus took ten years to reach a length of 1cm. Extrapolating this result to the Drayton sample, the largest specimen of this genus recovered from samples was 7mm long.

3. Nearly all of the species are sessile epibenthos and there is no development of tiered ichno- or biocoenoses.

4. Asteroid remains have been broken but have not been completely disarticulated by bioturbation, suggesting that the sediment had not been thoroughly worked before deposition of the next unit, or that a vagile infauna usually failed to establish.

Sedimentary processes

The thin sedimentary units are interpreted as being allochthonous chalks. The intervening hiatuses (months to less than a decade timescale?) were too short for a mature community to develop resulting in a high average sedimentation rate. The mechanism for controlling the source, frequency and volume of sediment influxes is unknown, but may have been smaller scale and more local in its operation than that suggested for Whitlingham (q.v.).

PALAEOENVIRONMENTAL INTERPRETATION: WHITLINGHAM

What is there to explain?

The chalk at Whitlingham displays widely but regularly spaced omission surfaces, separating thick units of a very poorly cemented, soft white chalk with an impoverished ichnofauna. Some omission surfaces have thick tabulate flint bands developed beneath them, and there are occasional, large paramoudras. Nodular chalks and hardgrounds are absent, and there is no evidence of winnowed horizons. Invertebrate fossils are well preserved and show no signs of physical abrasion, though evidence of bioerosion, especially of belemnite guards and their associated epifauna is commonplace. The fauna, mainly sessile benthos, was diverse, utilised a wide range of ecological niches, was not dominated by only a few members of the community, and was very sparse.

Energy of the environment

The absence of nodular chalks and hardgrounds implies that bottom currents were never strong enough to initiate their formation during hiatuses. The presence of a diverse suite of delicate, thin-valved lamellibranchs, and the well-preserved, unworn nature of the majority of the fossils, especially those taxa encrusting fragmentary invertebrate remains, further emphasises that the bottom conditions were usually quiescent. However, the sediment is well-mixed, as shown by the absence of articulated asteroid or crinoid ossicles and the

fragmented condition of the more delicate bivalves. The important bioturbating taxa that are normally responsible for this condition, thalassinid crustacea in particular, are absent at Whitlingham: there are no burrow-flints or other traces of their activities. Furthermore, *Hagenowia*, which has an antipathetic relationship with these crustaceans, (Gale & Smith, 1982) occurs regularly if sparingly.

Substrate conditions

The exceptionally soft, poorly cemented facies implies very soft bottom conditions. The absence of a diverse suite of small species of primary sessile epibenthos, especially bryozoa (as found at Drayton), suggests that the sediment had a thin (circa 5mm) layer immediately above the substrate with a large amount of sediment in suspension that precluded filter-feeding taxa. However, this turbid layer was not thick enough to exclude large terebratulids, such as *Carneithyris*, which Surlyk (1972) interpreted as having been free-living as adults. At times the turbid layer was thin enough to permit lunulitiform bryozoa (e.g. *Lunulites cretacea*, *Stichocados verruculosus*) and small solitary corals (*Stephanophyllia*) to colonise its surface. The apparent absence of a substantial infauna, whose activities contribute to the dewatering of sediments may be part of the explanation. Their absence in turn may be a function of the sedimentation rate: the units are believed to have been deposited as individual debris flows which, prior to dewatering may have been as much as twice their current average thickness of 0.5 m. It may be that the sediment was too incohesive to allow the construction of normal open tunnel systems such as those produced by thalassinid crustaceans, (soupground conditions, *sensu* Ekdale, 1985).

Length of time represented by hiatuses

The presence of some substantial tabulate flint bands provides one of several constraints on the minimum length of time represented by the omission surfaces. One of the major sources of the silica that forms flints are the spicules of hexactinellid sponges, which today are at their most abundant in calm, deep water (greater than 600m, Reid 1968). Clearly, conditions must have favoured their growth long enough for sufficient silica to accumulate to form these flints. (The silica content of a major sediment influx, derived from shallower water, higher energy environments would probably have been insignificant - see discussion below.)

Further clues to the length of time represented by hiatuses are the presence of a diverse suite of stalked crinoids (*Austinocrinus*, *Nielsenicrinus* and *Bourgueticrinus*), and of large species of inoceramid bivalves, all of which would presumably have required several seasons to attain maturity. (The author's collecting reveals that *Austinocrinus* may reach at least 0.3m in height.) At 5-7mm in diameter the stem ossicle specimens of *Nielsenicrinus* and *Bourgueticrinus* are of a modest size.

Sedimentary processes

The thick sedimentary units at Whitlingham are interpreted as being the product of high volume debris flows. The hiatus between flows is interpreted as being lengthy because the fauna had developed into a mature community (discussed further below).

The associated fauna is consistent with the inferred sedimentary regime, and the very low fossil content of the chalk and the dissociated state of the echinoderm remains becomes readily understandable if the preservable elements of the benthic community were 'diluted' by a succession of major sediment flows.

PALAEOECOLOGICAL INTERPRETATION: DRAYTON

Diversity

This site produced 136 species, including representatives of all the common invertebrate phyla (Table 1). Bryozoans (79 species, 58.1%) dominate the diversity, though brachiopods (14 species, 10.3%), echinoderms (13 species, 9.6%) and bivalves (12 species, 8.8%) are well represented.

The actual number of brachiopod and bivalve species is typical of what bulk sampling yields. (Compared with Whitlingham, the brachiopods include fewer encrusters, and no really large species, i.e. *Carneithyris*. The bivalves include fewer pectinids and limids - groups which include active swimmers.) There are 47 species (4 brachiopods, 6 bivalves, 1 cephalopod, 2 regular echinoids, 1 ophiuroid, 1 crinoid, 32 bryozoa) that are represented by a single specimen, and are adjudged to be rare. The core figure of 89 species left if these are subtracted from the total diversity is modest (especially when compared with the sparsely fossiliferous Whitlingham site (q.v.)), and is adjudged to represent a restricted fauna.

Table 1. Summary data for Drayton temporary section. Number of species (diversity) and number of individuals (density) of each phylum recovered are shown as actual numbers and percentage of total.

Phylum	**Diversity**	**%**	**Density**	**%**
Porifera	4	2.9	174	8.3
Anthozoa	4	2.9	34	1.6
Brachiopoda	14	10.3	103	4.9
Bivalvia	12	8.8	40	1.9
Cephalopoda	2	1.5	4	0.2
Echinodermata	13	9.6	431	20.5
Cirripedia	2	1.5	4	0.2
Crustacea	0	0.0	0	0.0
Serpulida	6	4.4	325	15.5
Bryozoa	79	58.1	987	47.0
TOTALS	**136**		**2102**	
Class level breakdown of echinodermata				
Echinoidea	5	38	167	39
Crinoidea	2	15	41	9.5
Ophiuroidea	1	7.7	12	2.8
Asteroidea	5	38	211	49
Comatulida	0	0	0	0
TOTALS	**13**		**431**	
Ordinal/sub-ordinal level breakdown of bryozoan figures:				
Bryozoa, (Cyclostomata)	24	32	391	39.6
Bryozoa, (Anasca)	16	21	296	30
Bryozoa, (Coilostega)	26	29	238	24
Bryozoa, (Cribrimorpha)	9	12	48	4.9
Bryozoa, (Ascophora)	4	5.3	14	1.4
TOTALS	**79**		**987**	

Density

Dominant and abundant taxa

Table 1 shows that Porifera are as abundant here as at any horizon investigated in the Norfolk Upper Campanian (8.3%, range: 2.3-8.3%), as are the Serpulida (15.5%, range: 6.4-15.5%). The Echinodermata are well represented (20.5%, range: 20.5-34.1%), but the class level contributions are distinctive and atypical: the Asteroidea make the greatest contribution (10.0%, range: 5.7-12.9%), followed by the Echinoidea (7.9%, range: 7.0-23%), Crinoidea (1.9%, range: 1.3-3.3%) and the Ophiuroidea (0.6%, range: 0.1-5%). Amongst the Echinoidea, 91% of the specimens are attributable to regular echinoids and only 9% to irregular echinoids, but they are collectively quite scarce (7.9% of the total fauna).

The fauna has three dominant taxa: *Glomerula gordialis*, asteroids (mainly *Metopaster* spp.) and *"Biflustra" pauperata* that account for 30.4% of the specimens. *Temnocidaris* spp., *Porosphaera* spp., and *Pustulopora* spp., are very abundant, and the following bryozoa are abundant: *Clausa globulosa*, "?*Hiantopora*" sp. nov. (1) and *Meliceritites* sp.; together they account for a further 28.6% of the fauna.

Niche occupancy

Primary sessile epibenthos

Of the ten dominant and abundant taxa, eight (*G. gordialis*, "*Biflustra*" *pauperata*, *Porosphaera* spp.[3], *Pustulopora* spp.[3]) are members of the primary sessile epibenthos. Amongst common taxa; 10 of 13 (*Petalopora* [*Sparsicava*] sp., *Bourgueticrinus* sp., *Terebratulina* spp.[3], *Onychocella strumulosa*, *Latereschara galeata*, *Infundibulipora* sp. *Volviflustrellaria taverensis* and *Isocrania costata*) are members of the sessile epibenthos. Of these, only the scarce crinoid *Bourgueticrinus* would have extended any distance above the sea floor, all of the other taxa would have been restricted to feeding in the bottom-most layer of the water column. Despite this, these species clearly thrived, and were present in prodigious numbers, forming a dense carpet ~1cm thick above the substrate.

The presence of sponges can be inferred from the limited fauna of spirorbid worms, corals and bryozoan colonies that utilised their spicules as a substrate. These encrusters harbour narrow cylindrical tubes in their skeletons, open at either end, where spicules used

to be. Flint preserved specimens suggest that these were all small forms (<5cm tall). In total, 82 of 136 species are primary sessile epibenthos.

Secondary sessile epibenthos (encrusters)

None of the dominant taxa are encrusters; 6 common taxa (*Filogramula cincta*, *Porosphaera sessilis*, *Onychocella inelegans*, *Onychocella norfolcia* and *Neomicrorbis crenatostriatus*) are encrusters, or at least had an encrusting base. Both of the serpulids utilised slender cylindrical substrates (sponge spicules); *P. sessilis* and *O.* spp. used a variety of different and often perishable substrates.

Large asteroids were common, however, unlike irregular echinoids, they rapidly disintegrate *post-mortem* into their constituent ossicles which are neither large enough nor stable enough to make attractive substrates. Common live substrates such as the tubes of *G. gordialis* are too small, and in any case subject to repeated reorientation since the animal grows by a form of self-encrustation. Hence, the encrusters belong to species that were either intrinsically small or are represented only by juveniles. They are nonetheless diverse (50 species); their larvae were reaching the region, but failed to thrive.

Vagile epibenthos

Asteroids

Asteroids (chiefly *Metopaster*) are very common at Drayton. On the basis of the width of marginal ossicles (15mm), *Metopaster* reaches the largest size recorded locally by the author for the genus, and all growth stages are present.

Regular echinoids

The radioles of *Temnocidaris* are as thick here as anywhere in the late Campanian (4.5mm). However, these may not have come from large tests, since test plates recovered are not exceptionally large. It seems more likely that these robust spines were an ecophenotypic response.

Irregular echinoids

Irregular echinoids are usually a common and conspicuous element of the vagile benthos in the *mucronata* zone. Overall, echinoids are scarce at Drayton, less than 8% of the washing

residue being test material, *versus* 22.6% at Whitlingham, and an average of 15%. Burrowing echinoids are entirely absent. *Echinocorys* is common at a well defined horizon in a pit (at TG 175 132) not far the temporary section (Peake & Hancock, 1961, 1972), but is very scarce in the samples, contributing only 9% of the total echinoid specimens. If *Echinocorys* is represented only because samples managed to include chalk from this horizon then the irregular echinoids were even scarcer than the figures suggest. The *Echinocorys* that are present belong to one of the smaller forms known from the Chalk: *Echinocorys ex groupa "conica"*. This may be because the *Echinocorys* population at this horizon was responding to an environment liable to frequent, major sedimentary influxes by maturing at a small size. Bored serpulid worm tubes testify to the presence of predatory gastropods.

Infauna

A sparse infauna was developed at two horizons. It seems to have been restricted to the crustacean *Callianassa* (represented by their burrows, the trace fossil *Thalassinoides*).

Morphological adaptations

Capitate bryozoan colonies

Amongst the cyclostome bryozoa there is an unusual preponderance of capitate forms from several different families: *Clausa globulosa*, *Bicavea striata*, *Osculipora truncata*, *Trochiliopora ?nuciformis* and *Clypeina rosula*. These five species represent 32% of the cyclostome faunal diversity and nearly 13% of the bryozoa fauna. Collectively, these classify as 'very abundant' at Drayton. More typical values involving the same taxa (which range throughout much of the Upper Campanian and Maastrichtian) would be 4% of the cyclostome fauna, 1.7% of the total bryozoan fauna and 1.0% of the total fauna (Whittlesea, unpublished data).

The maximum size of the commonest serpulid *G. gordialis*, is similar to the maximum size of these bryozoan colonies. Moreover, the capitate bryozoan colonies and the bead-like serpulid share a similar gross morphology.

Lunulitiform and Pavolunulitiform bryozoan colonies

Lunulitiform bryozoa have very low conical colonies that either rested directly on the sea-floor, or were supported by marginal setae that elevated them very slightly above the substrate. Some *Lunulites* taxa are capable of movement using marginal setae, and are thus able to exhume or "right" themselves if buried by minor sediment incursions. Pavolunulitiform bryozoa have fan-shaped colonies that are attached to a substrate that keeps them well clear of the sediment-water interface.

By British Late Cretaceous standards, lunulitiform bryozoa are exceptionally diverse at Drayton. At least eleven species are present *Volviflustrellaria taverensis*, *Lunulites tenax*, (four of the *Lunulites* have not yet been determined to species), and a ?*Lunulities* with five peri-ancestrula autozooids from which rows of autozooecia spiral outwards, and the arachnopusiid *Stichocados verruculosus*. (High diversity bryozoan faunas are not unusual *per se*.) Pavolunulitiform bryozoa include "?*Hiantopora*" sp. nov. (1), and two *Pavolunulites* sp.. Collectively, they represent 24% of the cheilostome bryozoan fauna and are an abundant element of the total fauna. More typical figures from the lower third of the Weybourne Chalk are three species comprising 1.3% of the cheilostome bryozoan fauna and 0.4% of the total fauna. The abundance of lunulitiform taxa has important palaeoenvironmental implications (as discussed above).

The "*Hiantopora*" spp. nov. are anascan bryozoans with large, palmate spines around the mural rim. (They certainly are *not Hiantopora* spp. s.s..) "*H.*" sp. nov. (1) differs from "*H.*" sp. nov. (2) in just two particulars: the colony of the former has small autozooecia (Lz = 0.54mm) and a pavolunulitiform colony while the latter has larger autozooecia (Lz = 0.63mm) and a vinculariform colony. The two populations can be interpreted either as morphological adaptations by the same species to different [?sub-] niches, or as different taxa. These taxa are common at Drayton and in the middle Weybourne Chalk at Eaton.

Summary

Drayton is interpreted as a warm (>12°C), shallow-water environment (80-200m), liable to frequent (months to less than a decade?) low-volume sediment influxes that smothered large areas of the sea-floor preserving a succession of pioneer communities.

After each influx, the sediment rapidly settled to provide a firm substrate without a suspension layer above it. This was colonised by a suite of mostly small species, of which the free-living serpulid *Glomerula gordialis* was dominant, although specialised cyclostome, anascan and coilostegan bryozoans thrived too. Small sponges were present, and their spicules supported a limited fauna of spirorbid worms, corals and bryozoan colonies.

The asteroids attained a large size. This may have been because in the absence of any competition, and with a rich source of food to prey on, they grew exceptionally quickly between influxes. Alternatively, they may have been able to survive the more minor influxes. Their large size may thus be due to a combination of being able to regain the surface when covered, and lack of competition from other large vagile benthos.

A further effect of the frequency with which the influxes arrived was to constrain the community from developing beyond the pioneer stage; nearly all the fauna is sessile filter-feeding epibenthos that fed in the bottom 1cm of the water column. Despite these apparent constraints, the resultant community was intensely productive, at times sufficiently so to produce a synsedimentary marl band. Rapid, gentle burial has probably preserved a succession of biocoenoses.

PALAEOECOLOGICAL INTERPRETATION: WHITLINGHAM

Diversity

This site produced 152 species including representatives of all the common invertebrate phyla (Table 2). Bryozoans (84 species, 55.3%) dominate the diversity, echinoderms (16 species, 10.5%) are exceptionally diverse, as are serpulids (11 species, 7.2%), and bivalves (16 species, 10.5%). Brachiopods (15 species, 9.9%) are also well represented.

The number of echinoderm species is as large as has been recorded anywhere in the Norfolk Upper Campanian (16, range 12-16), as is the number of serpulid species (11, range: 6-11), and the number of bivalve species (16, range:12-16).

There are 51 species (7 brachiopods, 6 bivalves, 1 ammonite, 2 cirripedes, 3 serpulids, 32 bryozoa) that are represented by a single specimen, and are adjudged to be rare. The core figure of 101 species left if these are subtracted from the total diversity is still high and Whitlingham is therefore adjudged to be a high diversity fauna.

Table 2. Summary for Whitlingham Sewage Works, temporary section. Number of species (diversity) and number of individuals (density) of each phylum recovered are shown as actual numbers and percentage of total.

Phylum	**Diversity**	**%**	**Density**	**%**
Porifera	2	1.3	49	3.4
Anthozoa	3	2.0	25	1.8
Brachiopoda	15	9.9	78	5.5
Bivalvia	16	10.5	110	7.7
Cephalopoda	1	0.7	2	0.1
Echinodermata	16	10.5	491	34.5
Cirripedia	4	2.6	9	0.6
Crustacea	0	0.0	0	0.0
Serpulida	11	7.2	96	6.8
Bryozoa	84	55.3	563	39.6
TOTALS:	**152**		**1423**	
Class level breakdown of echinodermata figures:				
Echinoidea	8	50	331	67.4
Crinoidea	5	31.3	75	15.3
Ophiuroidea	1	6.3	1	0.02
Asteroidea	1	6.3	83	16.9
Comatulida	1	6.3	1	0.02
TOTALS	**16**		**491**	
Ordinal/Sub-ordinal level breakdown of bryozoan figures:				
Bryozoa (Cyclostomata)	25	30	193	34.3
Bryozoa (Anasca)	14	16.6	102	18.1
Bryozoa (Coilostega)	17	20.2	195	34.6
Bryozoa (Cribrimorpha)	14	16.6	39	6.9
Bryozoa (Ascophora)	14	16.6	34	6.0
TOTALS	**84**		**563**	

Density

Dominant and abundant taxa

Table 2 shows that echinoderms are exceptionally abundant (34.5%, range 20.4-34.5%) and the bivalves are very well represented (7.7%, range: 1.0-7.7%). The class level contributions of the echinoderm figures are distinctive: echinoids (23.3%, range: 7.9-23.3%), asteroids (5.8%, range: 5.8-12.9%) and crinoids (5.3%, range: 1.3-5.3%). Amongst the echinoids, 88.8% are irregular echinoids, and 11.2% are regular echinoids (the exact opposite of Drayton). Asteroids are relatively scarce, and crinoids are very well represented.

The fauna has no dominant taxa, though the following eleven taxa are abundant: *Cardiaster*, *Echinocorys*, *Crateraster* sp., "*Biflustra*" *argus*, *Meliceritites* sp., *Glomerula gordialis*, *Woodipora strumulosa*, *Onychocella rowei/mimosa*, *Petalopora marssoni*, *Inoceramus* sp., and *Pustulopora* spp.. These account for 49% of the fauna. Thirteen common taxa account for another 20.0%.

The larger number of species in the abundant and common categories, together with the absence of dominant taxa, is taken to be an indication that this environment was relatively stable, allowing a more diverse and disparate fauna to establish.

Niche occupancy

Primary sessile epibenthos

Of the thirteen abundant taxa, ten ("*Biflustra*" *argus*, *Meliceritites* sp., *Glomerula gordialis*, *Woodipora strumulosa*, *Onychocella rowei/mimosa*, *Petalopora marssoni*, *Inoceramus* sp., *Pustulopora* spp.) are members of the primary sessile epibenthos. Most of these taxa are small, but *Inoceramus* may reach a large size. Of the 14 common taxa, four (*Isocrania costata*, *Porosphaera globularis*, *Lunulites cretacea* and *Onychocella matrona*) are members of primary sessile epibenthos.

There are five crinoid taxa present indicating a very diverse fauna. Collectively, crinoids are common, and include some of the largest crinoids known from the chalk, though the stem ossicles recovered from samples clearly came from modest sized individuals. The massive tabulate flints indicate that there must have been a substantial population of hexactinellid sponges present.

The sessile epibenthos contains 75 species feeding from 2mm (*Stephanophyllia*) to ?300mm (*Austinocrinus*, *Nielsenicrinus*) above the substrate. They exhibit a wide range of lifestyles (pedunculate brachiopods and byssate bivalves, free-living brachiopods, bivalves and sponges, rooted sponges and crinoids, embedded serpulids) exploiting a greater range of the water column than the diminutive Drayton fauna could have done. There is also a comparatively large size range within each phylum: e.g. brachiopods *Rugia* (~2mm) to *Carneithyris* (25mm). The larger elements of the benthos provided a substrate for a diverse community of encrusters.

Secondary sessile epibenthos (encrusters)

Of the common taxa, six (*Neomicrorbis crenatostriatus*, *Porosphaera sessilis*, *Onychocella inelegans*, *Pycnodonte vesicularis*, "*Membranipora*" *hegamone*, *Phractoporella constrata*) are encrusters (at least as juveniles). Most of these are small taxa, though *Pycnodonte* may reach a large size (150mm).

A wider availability of permanent, large substrates produced a diverse community of encrusters. Favoured substrates included belemnite guards and sponges. The guards were used by the larger sheet-like bryozoans, often intensively as shown by more than one generation of overgrowth. Slender "guard" spicules on living sponges were used by many smaller taxa. Echinoid tests were not used as intensively as might be expected: these seem to have been rather fragile, breaking up quickly *post mortem*.

Vagile epibenthos

The vagile epibenthos is dominated by echinoderms, echinoids in particular. A small *Cardiaster* sp. and an *Echinocorys* sp. are both very abundant. *Crateraster* is also abundant, but individuals did not reach a great size. Irregular echinoids outnumber regular echinoids by a factor of ten, though their tests were not often used by encrusting organisms. This is the exact opposite ratio to that found at Drayton. It is not clear what aspect of the environment made it more amenable to echinoids than asteroids; they outnumber them 4:1, whereas at Drayton the ratio is 4:5.

Infauna

The irregular echinoid *Hagenowia* is scarce, as is the organism responsible for the trace fossil *Bathichnus paramoudrae*. *Micraster* is represented by a two small test fragments. Clearly, for whatever reason, the infaunal niche was not an attractive proposition in this unit or facies.

The failure to develop an infauna is characteristic of allochthonous chalks (Bromley & Ekdale, 1987) and is probably a result of the incohesive nature of the original fine-grained, watery ooze making the construction of tunnels impossible, (soupground conditions *sensu* Ekdale, 1985).

Morphological adaptations

The cyclostome bryozoan community is characterised by an abundance of large fan shaped colonies (29.5% of the specimens [6 of 25 species] at Whitlingham vs. 2.3% [2 of 24 species] at Drayton) and the total absence of short-stemed globular taxa typical of Drayton. This is largely a consequence of the availability of suitable biogenic substrates required by the species involved: *Eohornera* and *Retecava* both require a stable substrate well clear of the sea-floor on which to cement their holdfast.

Irregular echinoids outnumber regular echinoids by a factor of 9. This presumably reflects the suitability of the sediment ingesting lifestyle of the irregulars vs. the grazing lifestyle of the regulars. The ratio of cemented to free-living serpulids further underscores the unfavourable nature of the substrate and the desirability of getting away from it: 52% of serpulids are encrusters versus 27% at Drayton, (25% is typical of the middle Weybourne Chalk).

Summary

Whitlingham is interpreted as a cool (cooler than Drayton's inferred 12^{o}C+), deep water (>200m), environment, liable to regular (on a time scale of centuries rather than decades), high volume sediment influxes that preserved evidence of a sparse, high diversity, mature community. Each influx smothered and extinguished the community it interred.

These conditions were not particularly favourable to the contemporary biota: densities are amongst the lowest encountered in the upper Campanian (even allowing for the diluting effect of a sediment influx) and specimens belonging to large echinoderm taxa

attained only modest dimensions. The community was diverse and characterised by a noteworthy degree of equilibrium between taxa at the phylum level. The high diversity might reflect, though probably only to a small degree, the accumulation of taxa over a long period. More important was the establishment of slower growing taxa (sponges, crinoids) which then provided substrates for other species (tethered and pedunculate genera of bivalves and brachiopods, and encrusting bivalves). The absence of dominant taxa in the assemblage reflects the maturity of the community. The absence of thalassinid crustaceans may be a function of the inferred low cohesiveness of the substrate.

CONCLUSION

Comparison of Upper Campanian faunas recovered from two superficially similar facies at Drayton and Whitlingham has revealed significant differences. These are essentially unrelated to evolutionary events because the majority of the faunal elements found at the older of the two sites (Drayton) persist into the local Maastrichtian. This leads to the conclusion that environmental facies is the key factor responsible for the differences found.

Field identification of the environmental facies investigated here would rely upon noting the spacing of the omission surfaces and the presence or absence of thalassinid flint bands or paramoudras. This is not very satisfactory, and a greater understanding of the sedimentary regimes responsible for producing these and other similar facies is required in order to produce superior criteria for discriminating between them. Only then will it be possible to improve significantly upon the palaeo-environmental interpretations given here.

ACKNOWLEDGMENTS

I would like to thank the Anglian Water Authority for permission to visit Whitlingham sewage works during the engineering work, and Norman Peake and Peter Murphy for much fruitful discussion of the ideas reported here.

REFERENCES

BROMLEY. R. G. and EKDALE, A. A. 1987. Mass transport in European Cretaceous Chalk; fabric criteria for its recognition. *Sedimentology*, **34**, 1079-1092

CADEE G. C. 1975. Lunulitiform Bryozoa from the Guyana Shelf. *Netherlands Journal of Sea Research*, **9**, 320-343

COBBAN, W. A. and KENNEDY, W. J. 1992. Campanian *Trachyscaphites spiniger* ammonite fauna in north-west Texas. *Palaeontology*, **35**, 63-93.

COOK P. L. and CHIMONIDES P. J. 1983. A short history of the Lunulite Bryozoa. *Bulletin of Marine Science*, **33**, 556-581

EKDALE, A. A. 1985. Palaeoecology of the marine endobenthos. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **50**, 63-81

ERNST, H. 1982. The marl layer M 100 in the Maastrichtian of Hemmoor, an example of selective $CaCO_3$ solution. *Geologisches Jahrbuch, Series A*, **61**, 109-127

GALE, A. S. and SMITH, A. B. 1982. The palaeobiology of the Cretaceous irregular echinoids *Infulaster* and *Hagenowia*. *Palaeontology*, **25**, 11-42

PEAKE N. B. and HANCOCK J. M. 1961. *The Upper Cretaceous of Norfolk*. In Larwood, G.P. and Funnell, B.M., (Eds). The Geology of Norfolk. Transactions of the Norfolk and Norwich Naturalists Society, reprinted 1972 by the Geological Society of Norfolk with addenda and corrigenda.

REID R. E. H. 1968. Bathymetric distributions of *Calcarea* and *Hexactinellida* in the present day and the past. *Geological Magazine*, **105**, 546-559

SURLYK, F. 1972. Morphological adaptations and population structures of the Danish chalk brachiopods (Maastrichtian, U. Cret.) *Det Kongelige Danske Videnskabernes Selskab Biologiske Skrifter*, **19**, 1-57.

WHITTLESEA, P. S. 1996. Temporary Chalk Exposures in East Norfolk, (upper Upper Campanian, zone of *Belemnitella mucronata sensu lato*) 1989-90. *Bulletin of the Geological Society of Norfolk*, **43**, 3-24.

HOLOCENE VEGETATION AND SALINITY CHANGES IN THE UPPER BLYTH ESTUARY, SUFFOLK.

David S. Brew[*,1], Alexander G. Mitlehner[#,2] and Brian M. Funnell[*].

[*]School of Environmental Sciences, University of East Anglia, Norwich, Norfolk, NR4 7TJ.

[#]Postgraduate Unit of Micropalaeontology, Department of Geological Sciences, University College London, Gower St., London, WC1E 6BT.

[1]Present address: British Geological Survey, Keyworth, Nottingham, NG12 5GG.

[2]Present address: Department of Botany, The Natural History Museum, Cromwell Road, London, SW7 5BD.

ABSTRACT

The Holocene environmental history of the upper Blyth estuary, Suffolk, has been determined using stratigraphic evidence from pollen and diatoms. The succession is dominated by biogenic deposits, with an initial phase of peat deposition about 5000 ^{14}C yrs BP. An early phase of open freshwater conditions was succeeded by a mixed woodland community dominated by alder, oak and hazel. This was followed by a decrease in the representation of arboreal pollen and an increase in herb pollen, indicating a further period of open conditions. A tentative date of 3000 pollen yr s BP is assigned to this event based on the decline in Tilia. The appearance of significant aquatic pollen indicates the development of damper conditions followed by an increase in the numbers of estuarine herb taxa, reflecting higher water levels which culminated in the deposition of clay. During this transgressive phase an initial rise in groundwater level created fresh/brackish water conditions followed by marine submergence of the area. The present-day inland saline penetration (and tidal limit) in the Blyth estuary is the maximum achieved at any time during the Holocene. This contrasts with Broadland where the maximum penetration occurred about 2000 ^{14}C yrs BP. Variations in coastal physiography causing locally reduced tidal ranges in Broadland are thought to explain this difference. The sequence of events in the upper Blyth estuary is provisionally correlated with events further downstream.

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INTRODUCTION

The River Blyth flows into the smallest of several major estuaries situated along the coast of Suffolk in eastern England (Fig. 1). The Blyth estuary may be more correctly described as a former estuary because most of the present-day channel is controlled by various types of river defence. However, for 3 km downstream from Blythburgh, several breaks in the river embankments have allowed estuarine tidal-flat conditions to become established over what was previously reclaimed land (Fig. 1).

This paper examines the stratigraphy and Holocene development of the Blyth estuary upstream from Blythburgh (the upper Blyth). Preliminary analyses of core material and data collected by Kreiser (1984) and the Anglian Water Authority (unpublished data, 1976) show that upstream from the tidal area the Holocene stratigraphy is thin (maximum recorded thickness 7.30 m) and composed predominantly of peat overlain by a thin estuarine clay near Blythburgh (Fig. 2). Initially, the paper seeks to describe the local vegetational history of the upper Blyth until the advent of clay deposition. For this section we rely on pollen data from a core (M1, Mitlehner, 1989), complemented by macrofaunal studies on five other cores (BB1 to BB5, Fig. 1). Data from cores sunk by the Anglian Water Authority, the Peat Survey (unpublished data, 1983/84), Suffolk County Laboratory (unpublished data, 1987) and Kreiser (1984) (Fig. 1) are also utilised. The second section of the paper deals with the clay phase in more detail, using diatom assemblages from core M1 (Fig. 3). The timing of maximum inland penetration of saltwater in the Blyth Valley is compared with that in the Broadland valleys located between 15 km (River Waveney) and 30 km (River Yare) to the north.

FIELD METHODS

Core M1 was recovered using a 'Russian type' corer which causes minimal disturbance of the deposit. Manipulation of the corer becomes difficult through compacted and woody sediments, a problem which stopped the coring at 5.75 m depth, short of the base of the Holocene sequence. Six sub-cores were taken with adjustments being allowed for a 20 cm overlap between each sub-core to minimise the effects of contamination. Cores BB1 to BB5 were recovered using an 'Eijkelkamp type' extendable hand gouge auger. Samples from BB6 were recovered using a 'Minuteman' power driven rotary drill. One of the samples was radiocarbon dated. The sites of core M1 and BB6 were levelled relative to OD.

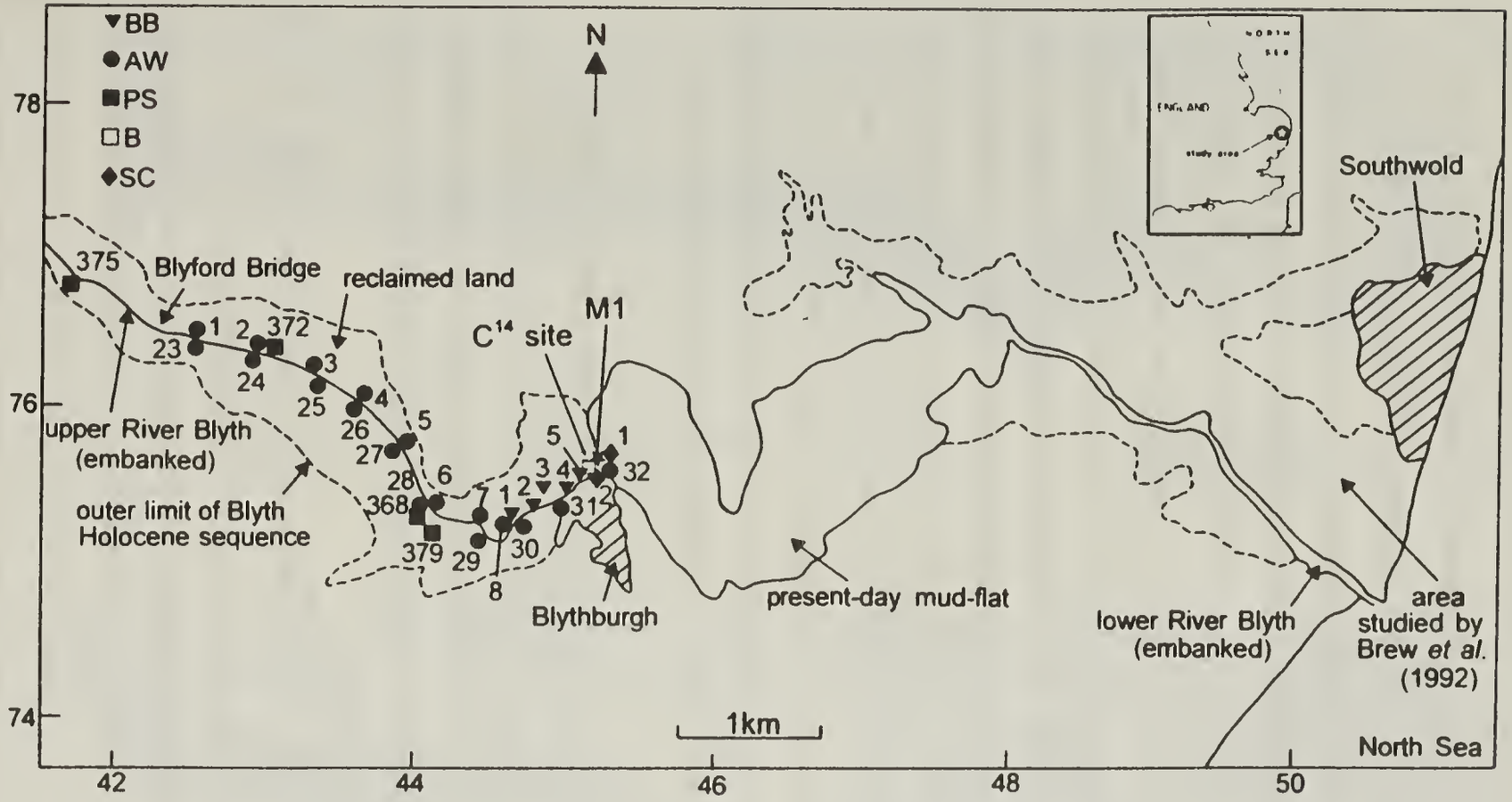


Fig. 1. Map of the upper Blyth estuary showing the locations of the core sites. BB=present study, AW=Anglian Water Authority, PS=Peat Survey, B=Kreiser (1984), SC=Suffolk County Laboratory. Note that downstream from Blythburgh, breaks in the river embankments have allowed re-establishment of tidal flat conditions.

GENERAL STRATIGRAPHY

Most of the cores upstream from Blythburgh show a similar stratigraphy comprising a basal grey or brown sand with flint gravel (a mid-Pleistocene beach plain deposit known as the Westleton Beds; Hey, 1967) overlain by peat of variable thickness (Figs. 2 and 3). The more downstream cores (BB2 to BB5, M1 and B4 especially) contain a unit of silty clay overlying the peat (Fig. 2). The silty clay unit thins upstream, disappearing just downstream of BB1.

Most of the Peat Survey cores are dominated by woody peat with, in most cases, between 5 and 50% of the wood remains constituting the deposit. However, some of the peat contains sedge and some contains greater than 50% wood remains. This stratigraphy is confirmed by both the present study and Kreiser (1984) who also found abundant freshwater molluscs towards the top of the peat in borehole B4. The wood is dominated by twigs and bark of *Alnus* (alder). Alder is an abundant and widespread tree species in Suffolk today, where it occupies wet woods, fens and carrs, or grows beside freshwater streams and rivers (Simpson, 1982). Huntley and Birks (1983) suggested that alder began to colonise these types of environment in south-east England early in the Holocene. The areal extent of alder carr was not restricted to the zone upstream from Blythburgh, but extended further east into the more downstream parts of the river. A single borehole at the seaward end of the River Blyth also contains peat with quantities of alder close to the Pleistocene Westleton Beds (Brew, 1990).

POLLEN AND DIATOM ANALYSES: LABORATORY PROCEDURES

A total of 32 samples were extracted from core M1 (Fig. 3), of which 20 were removed from the uppermost metre of the core. In addition to treating samples for pollen analysis, the uppermost clay was also examined for diatoms, whilst samples from the peat/clay transition were analysed for both pollen and diatoms.

The lowermost 25 samples were treated using the standard preparation for pollen extraction (Faegri and Iversen, 1989), including both Erdtman's acetolysis for cellulose removal and hydrofluoric acid (HF) treatment for the dissolution of colloidal silica. The residual solution was immersed in safranine-stained glycerol jelly before being mounted on labelled slides. Land pollen and pteridophyte grains were counted at each level, with aquatics and *Sphagnum* being recorded but not included in the final sum. Grains were counted at a standard magnification of x400, with identification being made with reference to type-slides and the key devised by Moore

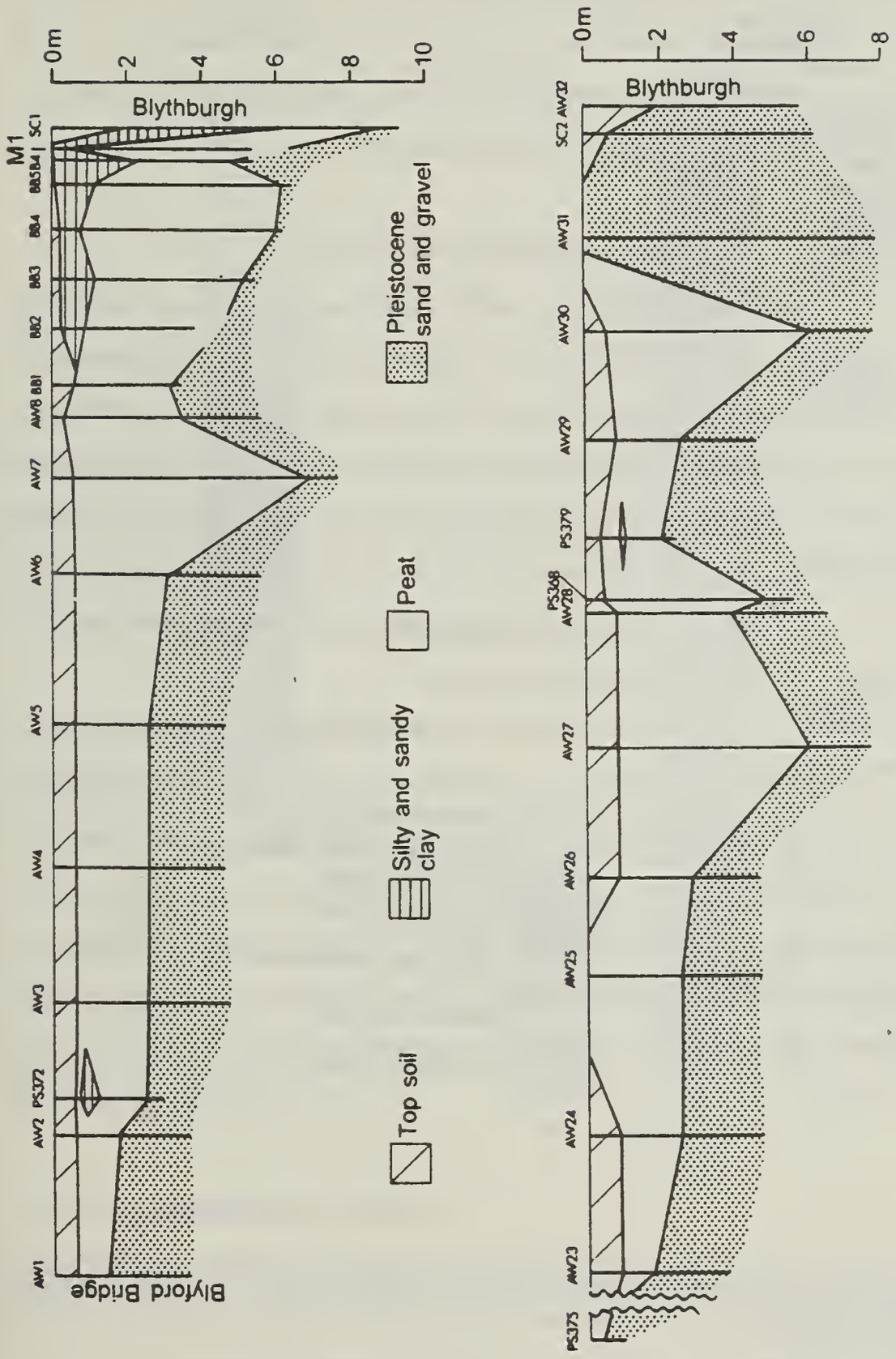


Fig. 2. Longitudinal sections along the north and south banks of the River Blyth from Blyford Bridge downstream to Blythburgh. Locations of core sites are shown in Figure 1.

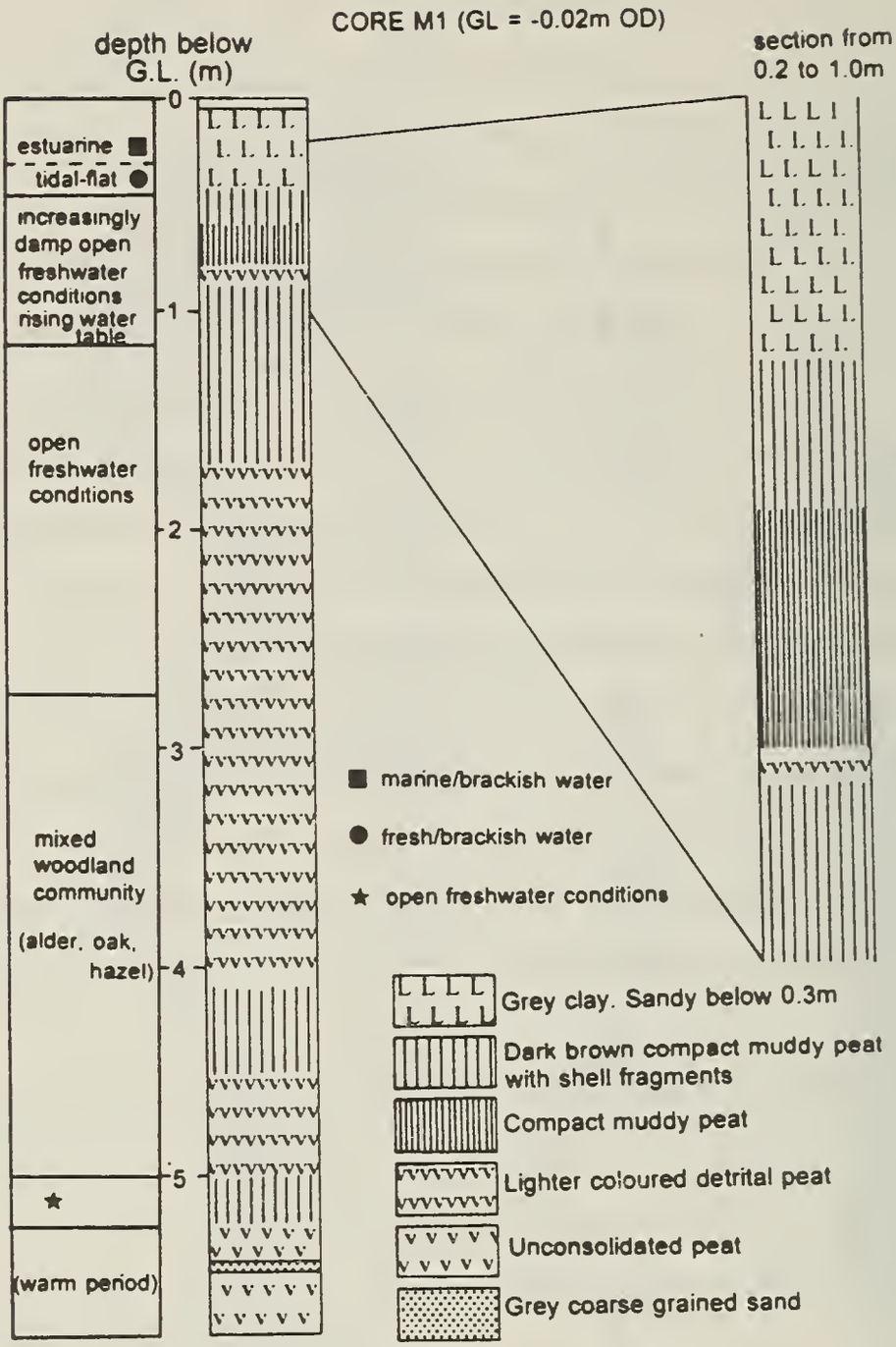


Fig. 3. Lithological description and palaeoenvironmental interpretation of core M1. Location of core site is shown in Figure 1.

and Webb (1978). Pollen percentages were calculated as a percentage of total land plus pteridophyte pollen.

The uppermost seven samples from the core were prepared for diatom analysis. This was carried out separately from the pollen analytical procedures as the latter HF treatment dissolves diatoms, while severe oxidation in the diatom procedures (involving hydrogen peroxide) removes all traces of pollen. Identification of the diatoms was undertaken with reference to the line drawings in the catalogues by Van der Werff and Huls (1958-1974).

POLLEN ASSEMBLAGES (Fig. 4)

The lithostratigraphic sequence obtained from core M1 (Fig. 3) shows that the Holocene history of sedimentation has been largely biogenic. Both micro- and macroscopic plant material show an abundance of *Alnus* through much of the sequence and a fen carr community is suggested as being present for much of the period prior to deposition of the uppermost clay. However, pollen spectra from the muddy peats show the presence of aquatic plants such as *Littorella* and *Potamogeton*, suggesting periods of increased groundwater levels leading to open freshwater conditions which are favoured by these species.

Local Pollen Assemblage Zone Bly-1.

***Alnus-Quercus-Corylus*-type (2.75-5.70 m, -2.77 to -5.72 m OD, Fig. 4)**

The basal pollen zone from Blythburgh shows low pollen frequencies, particularly below 4.08 m (-4.10 m OD). The zone is dominated by trees (48-72%) particularly *Alnus* (30-47%), *Quercus* (10-21%) and *Betula* (2-11%). *Tilia* pollen decreases from 7% to zero at the top of this zone, appearing again only at sporadic intervals higher in the core. Significant quantities of *Corylus*-type (3-18%) are also present. Filicales is significant towards the base of zone Bly-1 (12%) decreasing towards the top (1%).

Local Pollen Assemblage Zone Bly-2.

***Alnus-Quercus*-Gramineae-Cyperaceae (1.15-2.75 m, -1.17 to -2.77 m OD, Fig. 4)**

A reduction in both tree and shrub pollen and an increase in herb pollen characterise this zone. Trees are still dominant however, representing 38-56% of total land plus pteridophyte pollen, whereas herbs represent 25-42%. The quantity of *Alnus* falls to 22-32% as does the quantity of *Betula* to 3-5%. *Quercus* pollen numbers remain similar to zone Bly-1. *Corylus*-type pollen is

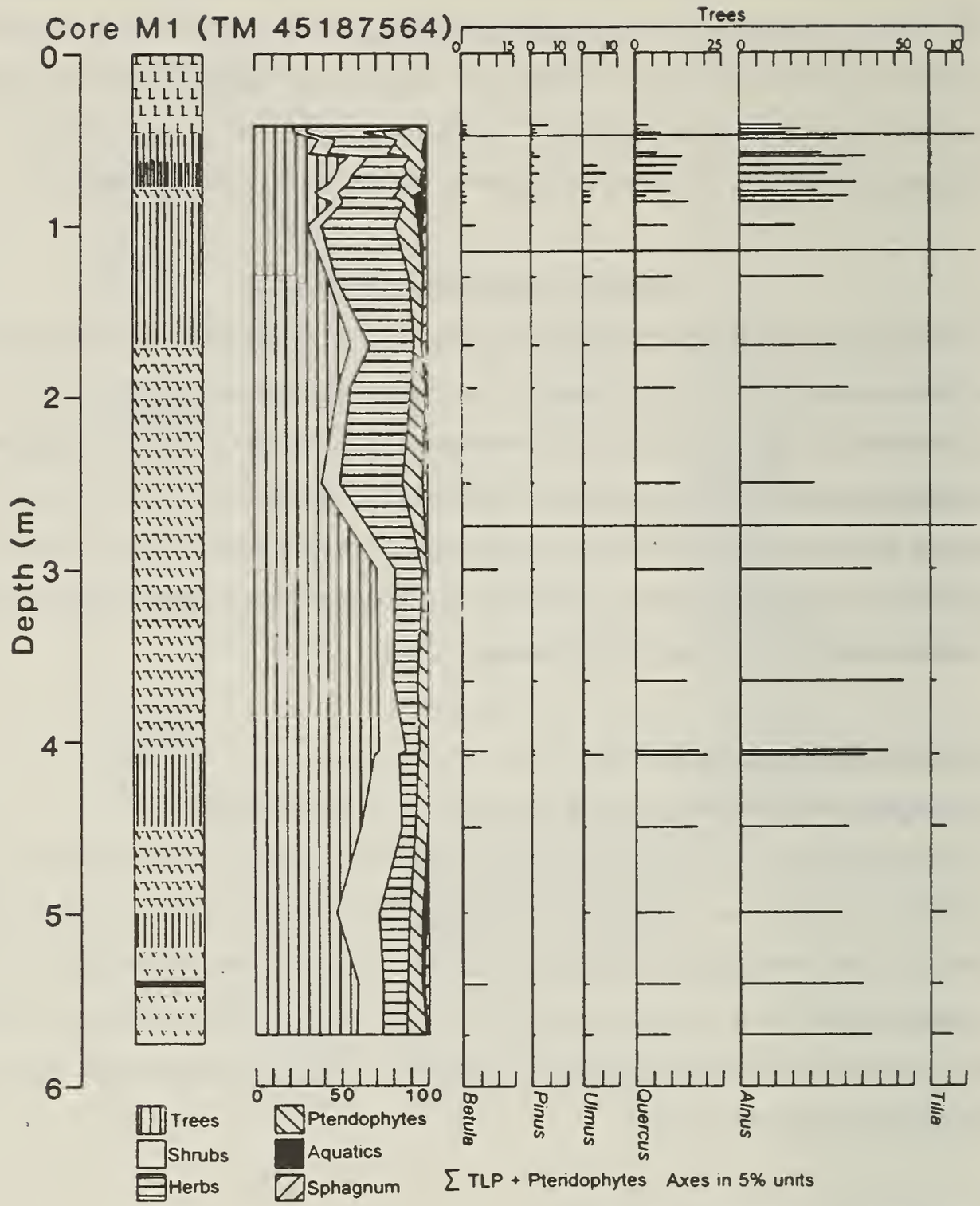
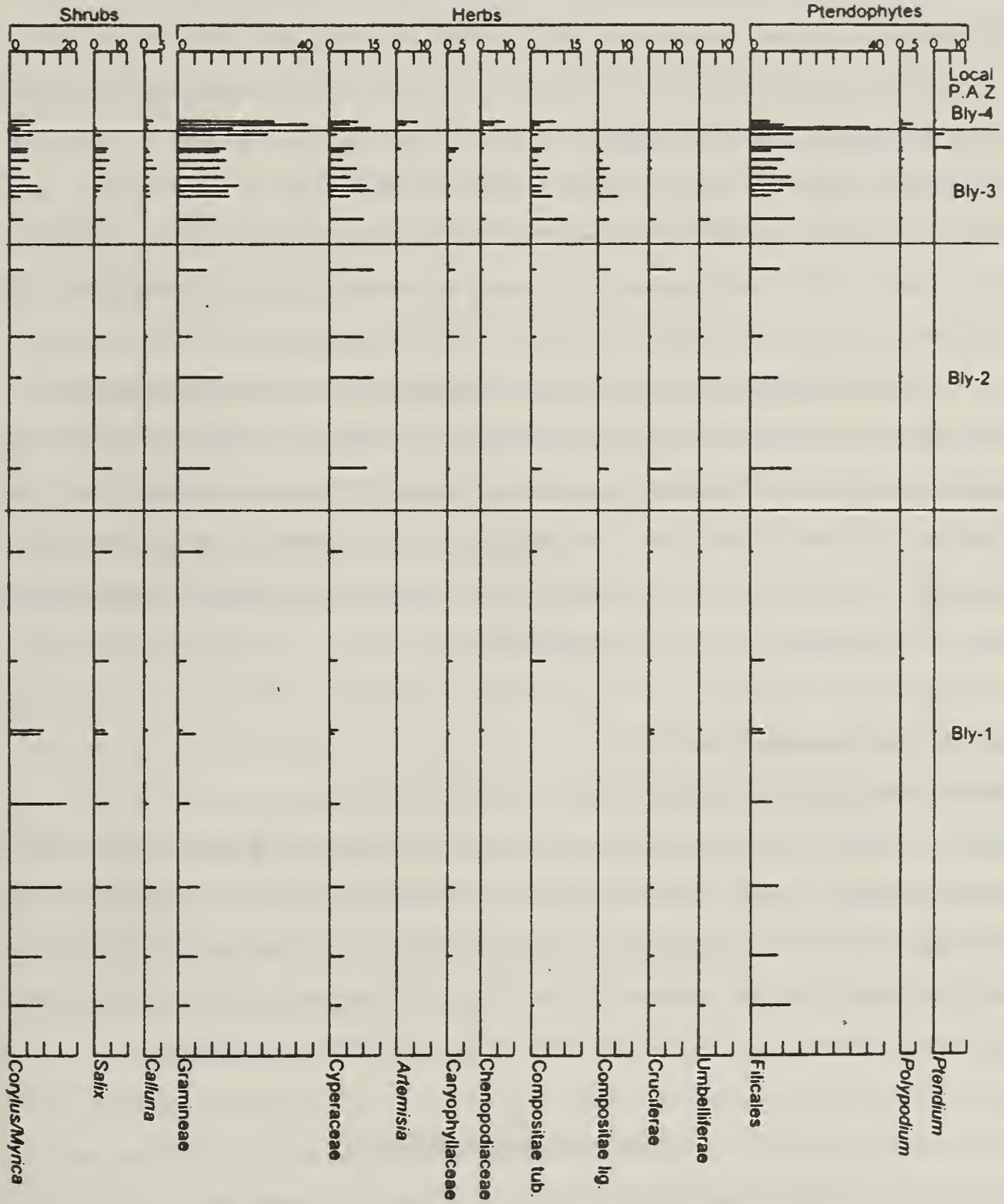


Fig. 4. Pollen diagram for core M1. Lithology symbols as Figure 3. Location of core site is shown in Figure 1. P.A.Z. = Pollen Assemblage Zone.


Shrubs
Herbs
Pteridophytes
Local P.A.Z
Bly-4
Bly-3
Bly-2
Bly-1
Pteridium
Polypodium
Filicales
Umbelliferae
Cruciferae
Compositae lig.
Compositae tub.
Chenopodiaceae
Caryophyllaceae
Artemisia
Cyperaceae
Gramineae
Calluna
Salix
Corylus/Myrica

reduced across the zone Bly1/Bly-2 boundary to 4-8%. The increase in herb pollen is due mainly to larger quantities of Gramineae (5-14%) and Cyperaceae (12-14%). In addition, Compositae (0-4%), Cruciferae (0-8%) and Umbelliferae (1-7%) make sporadic but increasing appearances.

Local Pollen Assemblage Zone Bly-3.

***Alnus-Quercus*-Gramineae (0.48-1.15 m, -0.50 to -1.17 m, Fig. 4)**

This zone is characterised by the first appearance of aquatic pollen (*Potamogeton*, 1-7%). Trees still dominate (32-55%) with generally little change in the abundance of individual species. The exceptions are *Betula* which falls to 1-2% and *Ulmus* which increases from 0-3% in zone Bly-2 to 3-7% but then disappears towards the top of zone Bly-3. Herbs also remain unchanged (25-43%) with Gramineae and Compositae increasing to 11-18% and 1-7% respectively while Cruciferae decrease to 0-1%. There is a gradual reduction of Cyperaceae numbers through zone Bly-3 from 11% at the base to 3% at the top with a further increase at the zone Bly-3/Bly-4 boundary. There is a small increase in pteridophyte numbers (predominantly Filicales increasing from 4-12% in zone Bly-2 to 7-14% in zone Bly-3).

Local Pollen Assemblage Zone Bly-4.

***Alnus*-Gramineae (0.42-0.48 cm, -0.44 to -0.50 m OD, Fig. 4)**

Most tree pollen types decrease in zone Bly-4 (23-24%), corresponding with a rise in frequencies of herb pollen (55-59%), particularly Gramineae (18-39%), Cyperaceae (6-12%), *Artemisia* (0-7%) and Chenopodiaceae (1-8%). Pteridophytes increase initially (to 38%), in particular Filicales but then decline at the top. Aquatic *Potamogeton*, which showed a rise in frequency at the beginning of zone Bly-3, is noticeably absent from zone Bly-4.

DIATOM ASSEMBLAGES

The uppermost clay from core M1 reveals diatoms of two main species assemblages. A distinct change in composition occurs at about 0.30 m depth (-0.32 m OD, sandy clay/clay boundary). At the base of the clay (0.44 m, -0.46 m OD) many intact and broken frustules of freshwater and brackish water diatoms are present, in particular those of *Pinnularia microstauron* which appear to form most of the clay matrix at this level. Between 0.42 and 0.35 m (-0.44 to -0.37 m OD) the diatom assemblages are dominated by oligohalobian (freshwater/brackish water) forms

including *Stauroneis phoenicenteron*, *Navicula peregrina*, *Navicula dicephela*, *Pinnularia* cf. *maior* and *Cocconeis placentula*.

At 0.30 m depth (-0.32 m OD), sand is the predominant component, with only sparse numbers of extremely corroded mesohalobian (marine/brackish water) diatoms. This may indicate a sudden influx of sediment. At 0.20 m depth (-0.22 m OD) an appreciable increase in the numbers of diatoms occurs together with an improvement in the state of preservation. By far the most common species at this level is *Diploneis interrupta* with significant quantities of *Actinoptychus undulatus*, *Coscinodiscus eccentricus* and *Nitzschia punctata* indicative of marine/brackish water conditions.

ENVIRONMENTAL CHANGE IN THE UPPER BLYTH ESTUARY

An unconsolidated peat at the base of core M1 between -5.77 and -5.23 m OD corresponds with the bottom of zone Bly-1. The peat contains *Alnus* and also *Tilia* suggesting a warm period. Although the base of the Holocene sequence was not reached in core M1, the onset of peat formation, resting on Pleistocene Westleton Beds, has been radiocarbon dated from borehole BB6, immediately upstream from Blythburgh (Fig. 1), as 4940±80 ^{14}C yrs BP (SRR-3486, c. -6.7 m OD). Sandwiched within this peat is a 2 cm layer of coarse grey sand (-5.44 to -5.42 m OD). The sand contains no microfossils but the roundness of grains suggests that it may have been waterlain. Alternatively, it may have been slopewash derived from the Westleton Beds which form high ground adjacent to the Blyth estuary. Above the basal peat is a more compacted muddy peat (-5.23 to -5.02 m OD) which contains aquatic pollen and freshwater shell remains suggesting open freshwater conditions. The lower part of an overlying detrital peat corresponds with a slight fall then a steady increase in arboreal pollen through zone Bly-1 (predominantly *Alnus* and *Quercus*). This may indicate that a mixed woodland community became established in the area. In the middle of the detrital peat (at -2.77 m OD) a sharp increase in the presence of herb taxa corresponds with almost complete disappearance of *Tilia* (junction of zones Bly-1 and Bly-2). A climatically induced change to more open conditions may have taken place at this time (West, 1980) and a minimum age of around c. 3000 pollen yrs BP is suggested based on the reduction in *Tilia*, a widely recognised event in the British post-glacial pollen record. It should, however, be emphasised that prehistoric forest clearance by Neolithic farmers may equally be responsible for this change in the pollen spectrum (Waller, 1994).

The pollen spectra in the base of the overlying muddy peat unit do not change significantly from the underlying detrital peat. However, at -1.17 m OD the transition to zone Bly-3 is marked by the appearance of aquatic plants indicating that increasingly damp conditions were introduced at this time. Zone Bly-4 shows a further rise in the percentage of herb taxa, in particular Gramineae, Cyperaceae, *Artemisia* and Chenopodiaceae. The latter pollen group is indicative of estuarine conditions and water table levels were probably rising at this time, culminating in a change to estuarine grey clay at -0.47 m OD. The peat/clay transgressive overlap is transitional and believed to be younger than 3000 yrs BP (ie. above the *Tilia* decline). The clay exhibits iron mottling and is tinted yellow below -0.32 m OD. The yellow coloration corresponds with the presence of sand (-0.47 to -0.32 m OD) within the base of the clay unit. Plant fragments preserved in the clay are predominantly *Phragmites*. Brackish water diatoms from the clay suggest marked changes in salinity occurred during its deposition. A fresh/brackish flora is present below -0.32 m OD, whereas a marine/brackish assemblage occurs above.

DISCUSSION

Comparison with downstream stratigraphy

In order to correlate the peat sequence upstream from Blythburgh with the sequence downstream from the present-day tidal area, a brief summary of the lower Blyth Holocene sequence is given. The sequence is dominated by clastic sediment intercalated with thinner peat units (Brew *et al.*, 1992). The succession comprises peat (Lower Peat), overlain by silt/clay (Lower Clay), a second peat (Middle Peat) and finally another silt/clay layer (Upper Clay). The Lower Clay represents a first phase of transgressive overlap onto an eroded Pleistocene or Lower Peat surface. Peat initiation has been dated at about 6755 ^{14}C yrs BP with the first inundation by silt/clay at about 6510 to 6385 ^{14}C yrs BP. A period of regressive overlap followed, represented by the Lower Clay\Middle Peat boundary (4575-4400 ^{14}C yrs BP) and a second transgressive overlap initiated the deposition of the Upper Clay on top of the Middle Peat (4300-4260 ^{14}C yrs BP).

The dominant four part stratigraphy of the lower Blyth (Brew *et al.*, 1992) is here tentatively correlated with changes in the peat stratigraphy of the upper Blyth. The lowermost muddy peat in core M1 grew in relatively higher groundwater conditions which occurred sometime after about 5000 ^{14}C yrs BP and may correlate (in part) with deposition of the Lower

Clay found in the lower Blyth. The lowering of groundwater levels and the development of a mixed woodland community upstream from Blythburgh may have coincided with the growth of the Middle Peat in the downstream areas. The exact time of establishment of estuarine clay deposition upstream from Blythburgh is unknown, but a minimum age of 3000 yrs BP is postulated based on the pollen data. In the lower Blyth the later transgressive overlap is at 4300/4260 ^{14}C yrs BP at an OD level of between -6.75 m and -4.55 m (Brew *et al.*, 1992). The establishment of estuarine conditions at -0.47 m OD upstream from Blythburgh is therefore believed to have occurred late in the history of the valley. The upper Blyth clay may represent the late Holocene inland maximum of the Upper Clay of the lower Blyth, before the upper Blyth was embanked. Once the embankments had been built, estuarine sedimentation was restricted to the channel only.

The upper Blyth clay is divided into two lithological units containing different diatom assemblages. From -0.47 to -0.32 m OD the clay is sandy and contains fresh/brackish water diatoms. Above -0.32 m OD, sand is absent and marine/brackish water diatoms dominate. The boundary between these two units is marked by a sand containing corroded marine/brackish water diatoms. A simple provisional model is proposed here to explain these changes in lithology and salinity during the transgressive phase in the upper Blyth. It is possible that, initially, the estuary was 'ponded' behind a coastal sand barrier which grew across the mouth of the Blyth. At that time the river's access to the sea would have been impeded, whilst gradual inundation of the peat sequence was taking place. This led to deposition of the fresh/brackish water sandy clay at -0.47 m OD. A combination of rising groundwater levels and increased marine erosion led to the eventual destruction of the barrier and the ingress of seawater into the valley, depositing the marine/brackish sand horizon at -0.32 m OD. A corresponding presence or absence of sand at this level in the lower Blyth is difficult to ascertain. The breaching of the barrier may well have occurred post-700 yrs BP, allowing the presence of a barrier up to this time as postulated by Parker (1978). After the influx of sand, estuarine conditions became established leading to the deposition of marine/brackish water clay.

In the upper Blyth Valley the estuarine clay unit overlying the main peat sequence thins upstream and eventually disappears downstream from BB1 (Figs. 1 and 2). The maximum inland extent of estuarine sedimentation during the earlier Holocene was therefore located immediately to the west of Blythburgh. Today, during high tides, salt water extends inland as far as Blyford Bridge (about 2.5km upstream from BB1, Fig. 1). Estuarine sedimentation would

presumably be taking place between Blythburgh and Blyford Bridge at the present-day if the river walls (embankments) were not present, suggesting that the present-day inland limit of salt water penetration (cf. estuarine sedimentation) is the maximum achieved at any time during the Holocene.

It is possible, however, that the width restriction of the estuary by embankments downstream from the present-day tidal-flat and upstream from Blythburgh (Fig. 1) may artificially induce a salt water limit further inland than an unembanked estuary. The Blyth is naturally bounded by high ground for 3 km downstream from Blythburgh (Fig. 1) and it is believed that this area dissipates much of the incoming tidal energy. The unperturbed salt water inland limit is therefore believed to be also located at, or just downstream from Blyford Bridge indicating that the transgressive overlap phase that began around 4300 ^{14}C yrs BP in the lower Blyth (Brew *et al.*, 1992) has continued to the present-day to reach Blyford Bridge. The diatom assemblages of the clay indicate increasing marine influence through time.

Comparison with Broadland estuaries

These results are significantly different from those of Coles and Funnell (1981) and Alderton (1983) for the Broadland (Yare/Waveney) valleys in east Norfolk. The maximum Holocene marine incursion in the Broadland valleys is believed to have occurred during the 'Romano-British' transgressive overlap between c. 2000 and 1500 ^{14}C yrs BP for the Yare Valley (Coles and Funnell, 1981) and 2600/1700 to 1700/1500 ^{14}C yrs BP for the Waveney Valley (Alderton, 1983), and not at the present day. In the Yare Valley extensive growth of peat has occurred post-1500 ^{14}C yrs BP (mainly at the valley edges), indicating that a regressive overlap had begun at this time (Coles and Funnell, 1981). This is in contrast to the Blyth Valley where the transgressive overlap registered in the lower Blyth at about 4300 ^{14}C yrs BP is thought to have continued up to the present-day without further peat growth.

Numerous factors may account for the different timings of maximum saline penetration in the Blyth and Yare valleys. These include differential sediment supply, sediment accumulation rates and subsidence between sites. However, we favour a mechanism controlled by long-term changes in tidal range, caused in part by the growth (Yare) and destruction (Blyth) of coastal spit systems over the last 1500 ^{14}C years. Prior to 700 yrs BP there were spits growing across the mouths of both the Yare and Blyth estuaries (Coles and Funnell, 1981; Parker, 1978). After this time the Blyth spit was destroyed, whereas the Yare spit is still in existence. The destruction

of the spit across the Blyth (post-700 yrs BP based on historical data, Parker, 1978) may be marked by the initial deposition of a marine/brackish water sand above the peat in the upper Blyth (ie. increasing the tidal range and causing a landward movement of the inland saline limit). In contrast the continued build-up of the spit across the mouth of the Yare is believed to have been partly responsible for a drop in tidal range in the enclosed estuary causing a regressive overlap (1500 ^{14}C yrs BP) and a seaward movement of the inland saline limit from its maximum penetration around 1600 ^{14}C yrs BP (Coles and Funnell, 1981). The persistence of the Yare spit up to the present day, in contrast to the open mouth of the Blyth estuary since c. 700 yrs BP (or later), continue to influence the timing of the inland saline maximum in each estuary.

CONCLUSIONS

Core data from the Blyth estuary upstream from Blythburgh, Suffolk, have shown that the Holocene stratigraphy is dominated by wood peat. Immediately above the Pleistocene surface the peat is rich in alder fragments which decline in abundance with decreasing age. The dominance of alder suggests initiation of a wooded freshwater environment similar to that fringing Broadland today. The timing of the first peat growth immediately upstream from Blythburgh has been dated at 4940±80 ^{14}C yrs BP (-6.7m OD). Pollen spectra from a single core (M1) at Blythburgh describe a period of open freshwater conditions, succeeded by a period of mixed woodland and followed in turn by further open conditions thought to have begun around c. 3000 pollen yrs BP. Rising water levels culminated in a marine inundation of the area, preserved as an estuarine clay. Diatom assemblages preserved in the clay indicate increasing marine influence through time with the present-day inland limit of estuarine sedimentation believed to be the maximum achieved at any time during the Holocene. This contrasts with the Broadland valleys where the maximum inland estuarine penetration took place earlier, during the so called Romano-British transgressive phase about 2000 ^{14}C yrs BP (Alderton, 1983; Coles and Funnell, 1981). The main reason for the difference appears to be a reduced tidal range in Broadland compared to the Blyth due to the growth and persistance of the Yare spit over the last c. 1500 ^{14}C years.

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REFERENCES

ALDERTON, A. 1983. *Flandrian Vegetational History And Sea-Level Change Of The Waveney Valley.* Unpublished PhD. Thesis., University of Cambridge., 379pp.

BREW D.S., FUNNELL B.M., and KREISER A. 1992. Sedimentary environments and Holocene evolution of the lower Blyth estuary, Suffolk (England) and a comparison with other East Anglian coastal sequences: *Proceedings of the Geologists' Association*, **103**, 57-74.

BREW, D.S. 1990. *Sedimentary Environments And Holocene Evolution Of The Suffolk Estuaries.* Unpublished PhD. Thesis., University of East Anglia., 286pp.

COLES B.P.L. and FUNNELL B.M. 1981. Holocene palaeoenvironments of Broadland, England: in Nio S.-D., Schuttenhelm R.T.E., and van Weering Tj.C.E., eds., 1981, Holocene marine sedimentation in the North Sea Basin: *Special Publication of the International Association of Sedimentologists*, **5**, 123-131.

FAEGRI, K. and IVERSEN, J. 1989. *Textbook Of Pollen Analysis*, 2nd edition. Wiley, Chichester, 328pp.

HEY, R.W. 1967. The Westleton Beds reconsidered. *Proceedings of the Geologists' Association*, **78**, 427-445.

HUNTLEY, B., and BIRKS, H.J.B. 1983. *An Atlas of Past and Present Pollen Maps of Europe: 0-13000 Years Ago.* Cambridge University Press., 667pp.

KREISER, A. 1984. *The Holocene Foraminifera And Palaeoenvironments Of The Blyth Estuary, Suffolk.* Unpublished BSc. project., University of East Anglia., 34pp.

MITLEHNER, A.G. 1989. *Flandrian Vegetational And Sea-Level Changes In The Blyth Valley, Suffolk.* Unpublished BSc. project., City of London Polytechnic., 43pp.

MOORE, P.D.,and WEBB, J.A. 1978. *An Illustrated Guide To Pollen Analysis.* Hodder and Stoughton, London., 133pp.

PARKER, R. 1978. *Men of Dunwich.* Collins, 272pp.

SIMPSON, F.W. 1982. *Simpson's Flora of Suffolk.* Suffolk Naturalists' Society, 537pp.

VAN DER WERFF, A., and HULS, H. 1958-1974. *Diatomeen Flora van Nederland*, Abcoude, Den Haag.

WALLER, M.P. 1994. Flandrian vegetational history of south-eastern England. Stratigraphy of the Brede valley and pollen data from Brede Bridge, *New Phytologist*, **126**, 369-392.

WEST, R.G. 1980. Pleistocene forest history in East Anglia. *New Phytologist*, **85**, 571-622.

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Copies of the Bulletin may be obtained from the Secretary at the address given above; it is issued free to members.

The illustration on the front cover is figure 2 from the article by Brew *et al.*, in this issue of the Bulletin. It shows longitudinal Holocene sections along the north and south banks of the River Blyth from Blyford Bridge downstream to Blythburgh, Suffolk.

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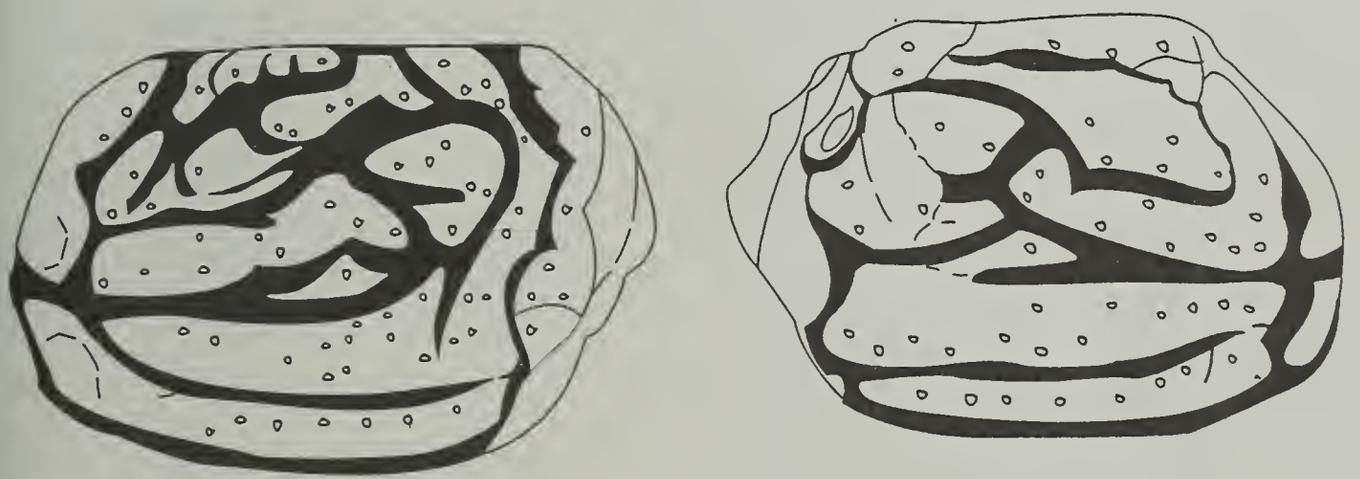
NO.44 for 1994



Schizocythere pliocenica

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Pliocene Ostracoda of the Walton Crag,
Walton-on-the-Naze,
Essex

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BULLETIN OF THE GEOLOGICAL SOCIETY OF NORFOLK

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Editor: Julian E. Andrews

School of Environmental Sciences,
University of East Anglia,
Norwich NR4 7TJ

Telephone 01603 592536
FAX 01603 507719
E-mail J.Andrews@uea.ac.uk

EDITORIAL

Bulletin No. 44 is dedicated to one large article written by Dr. Adrian Wood from Coventry University. This article describes formally the Ostracoda of the Walton Crag from the Naze Cliff, north of Walton-on-the-Naze in Essex.

I have enough material for another 50 page Bulletin, which is being assembled now (July 1996). Bulletin No. 45 should, therefore, appear by the end of 1996.

I am short of material for issues beyond Bulletin No. 45 and welcome the submission of papers on any aspect of East Anglian geology. My intention is to continue publishing approximately 50 page Bulletins in fairly rapid succession until the publication schedule is up to date.

BRN 30/3/18

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If possible, contributors should submit manuscripts as word-processor print out accompanied by a disk copy. We can handle most word-processing formats although PC Word, WordPerfect or ASCII files are preferred. In addition we accept typewritten copy and will consider legible handwritten material.

It is important that the style of the paper, in terms of overall format, capitalisation, punctuation, etc. conforms as strictly as possible to that used in Vol. 41 of the Bulletin. Titles and first order headings should be capitalised, centred and in bold print. Second order headings should be centred, bold and lower case. Text should be 1½ line spaced. All measurements should be given in metric units.

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The editors welcome original research papers, notes or comments, and review articles relevant to the geology of **East Anglia** as a whole, and do not restrict consideration to articles covering Norfolk alone. All papers are independently refereed by at least one reviewer.

PLIOCENE OSTRACODA OF EAST ANGLIA (PART I): THE WALTON CRAG AT WALTON-ON-THE-NAZE, ESSEX.

Wood A.M.

Centre for Quaternary Studies, School of Natural and Environmental Sciences, Coventry University, Priory Street, Coventry CV1 5FB

ABSTRACT

Four ostracod species were originally described by Jones (1857) from the Naze Cliff, north of Walton-on-the-Naze; type section for the Waltonian Red Crag (Harmer, 1900a). Twenty-five extinct species of Ostracoda, including one new species Thaerocythere epistylium sp. nov., are formally described from the same locality. The ostracod fauna represents a re-colonisation of expanding sub-littoral Waltonian niches by a low diversity, eurythermal, Coralline Crag remanie. Clear affinities exist in both the composition and number of extinct ostracod species within both the Coralline and Walton crags, which set them apart from the younger Newbourn and Butley Crag faunas. This evidence appears to support pre-eminent "crag" palaeontologists, such as Wood, S.V. snr (1866, 1872) and Harmer (1896) who have given serious thought to the separation of the Walton Crag from the Red Crag.

INTRODUCTION

A hundred and forty years have passed since Jones (1857) first published his monograph on the Tertiary Ostracoda of England. Of the eighteen species of ostracod he originally described from the Pliocene deposits of East Anglia, only four were known to occur in the Red Crag Formation at Walton-on-the-Naze (Table 1). Of these species only *Thaerocythere trachypora* (Jones, 1857) has been found during this present investigation; Jones' holotype of *Potamocypris tuberculata* appears to be missing from the Jones collection (at the Natural History Museum, London) and as yet no specimens of *?Cythere*

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Jones, 1857	Jones, 1870	Jones and Sherborn, 1889	Wood, herein
Cythere laqueata	*Cythere laqueata*	*?Cythere laqueata*	*Echinocythereis laqueata*
Cythere trachypora	*Cythere trachypora*	*Cythere trachypora*	*Thaerocythere trachypora*
Cythere (C.) tuberculata	*Cytheridеis tuberculata*	*Potamocypris tuberculata*	?missing from the Jones collection = ?*Eucythere* sp
Bairdia subdeltoidea, Münster	*Bairdia fusca* (?) Brady	*Bairdia fusca* (?) Brady	?*Bairdoppilata* sp. A

Table 1. Synonymy of Jones' (1857) original four Walton Crag ostracod species.

laqueata or *Bairdia fusca* (?) Brady, *sensu* Jones and Sherborn (1889) have been found at Walton-on-the-Naze.

Two additional species, *Palmoconcha tamarindus* (Jones, 1857) and *Pontocythere elongata* (Brady, 1868), were described by Jones and Sherborn (1889), however, no explicit sampling locality, other than "Red Crag" (?Walton or Butley Crag), was given.

References have been made to single species within the Red Crag Formation (Horne and Whittaker, 1983; Wouters, 1973) and, although a reconstruction of the Waltonian climate has been attempted using fossil-Recent ostracod analogues (Wood *et al.*, 1994), this paper represents the first of four detailed taxonomic investigations of the East Anglian (Pliocene) ostracod fauna. Three 1kg samples (W1, W2 and W3) were collected for micropalaeontological investigation from the Site of Special Scientific Interest at Naze Cliff section, north of Walton-on-the-Naze (TM265232-267243); type section for the Waltonian Red Crag (Funnell and West, 1977). The Naze Cliff sample locality, and the regional disposition of historically important crag localities are presented in Fig. 1.

A REVIEW OF THE WALTONIAN STRATIGRAPHY

Although initial lithological and faunal analyses of the East Anglian crags were undertaken by Charlesworth (1835, 1837) and Lyell (1839), the Naze Cliff section at Walton-on-the-Naze was first figured and examined in detail by Prestwich (1871). A stratigraphical section of the Naze Cliff, showing sedimentary structures and sampled horizons (W1-W3), can be seen in Fig. 2. The subsequent fifty years saw the summation of further lithostratigraphies (reviewed in Zalasiewicz and Mathers, 1985; Zalasiewicz *et al.*, 1988) which generally

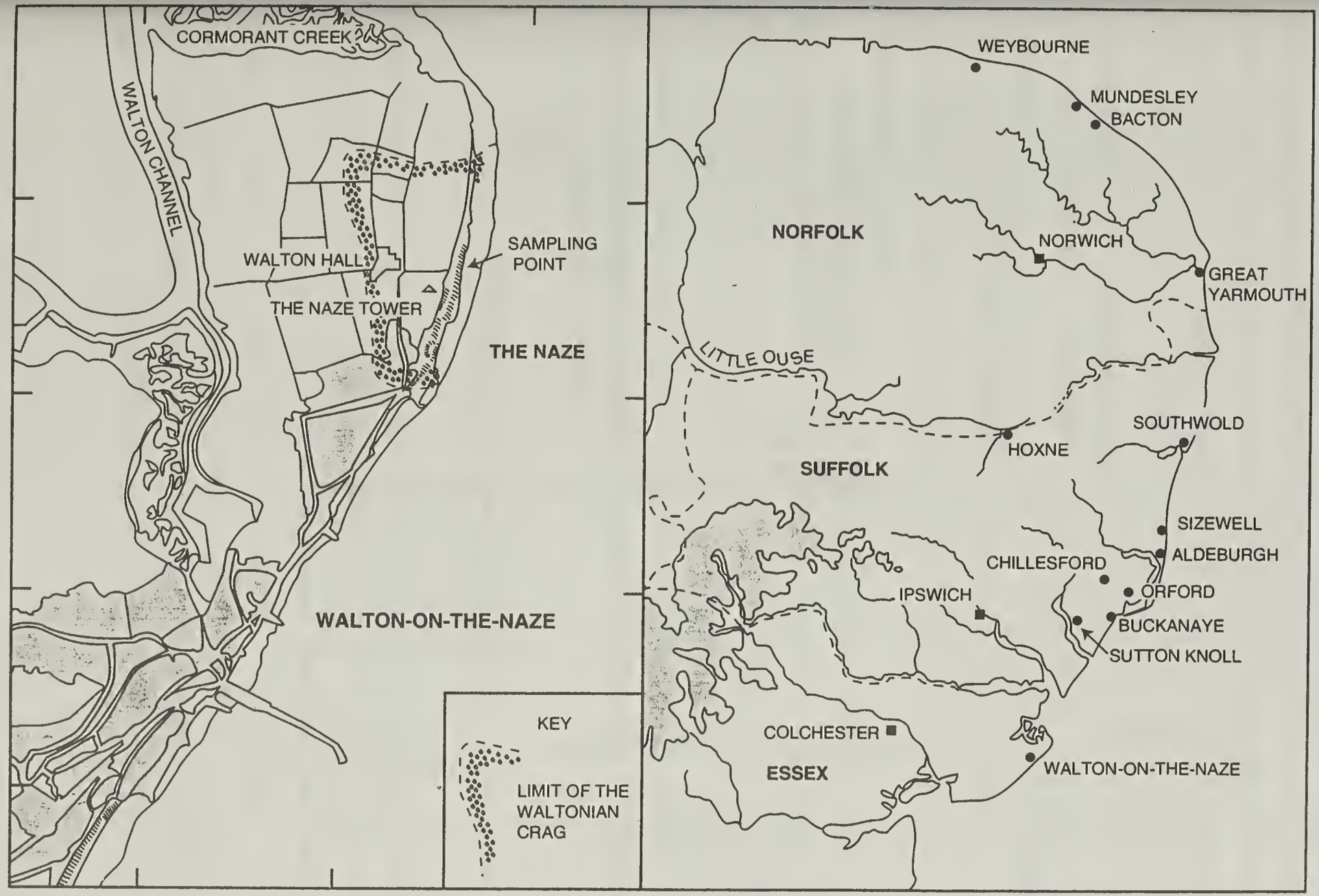

Fig. 1. Sample site location at the Naze Cliff, Walton-on-the-Naze (TM265232-267243) and the disposition of the more important Plio-Pleistocene "crag" localities in East Anglia.

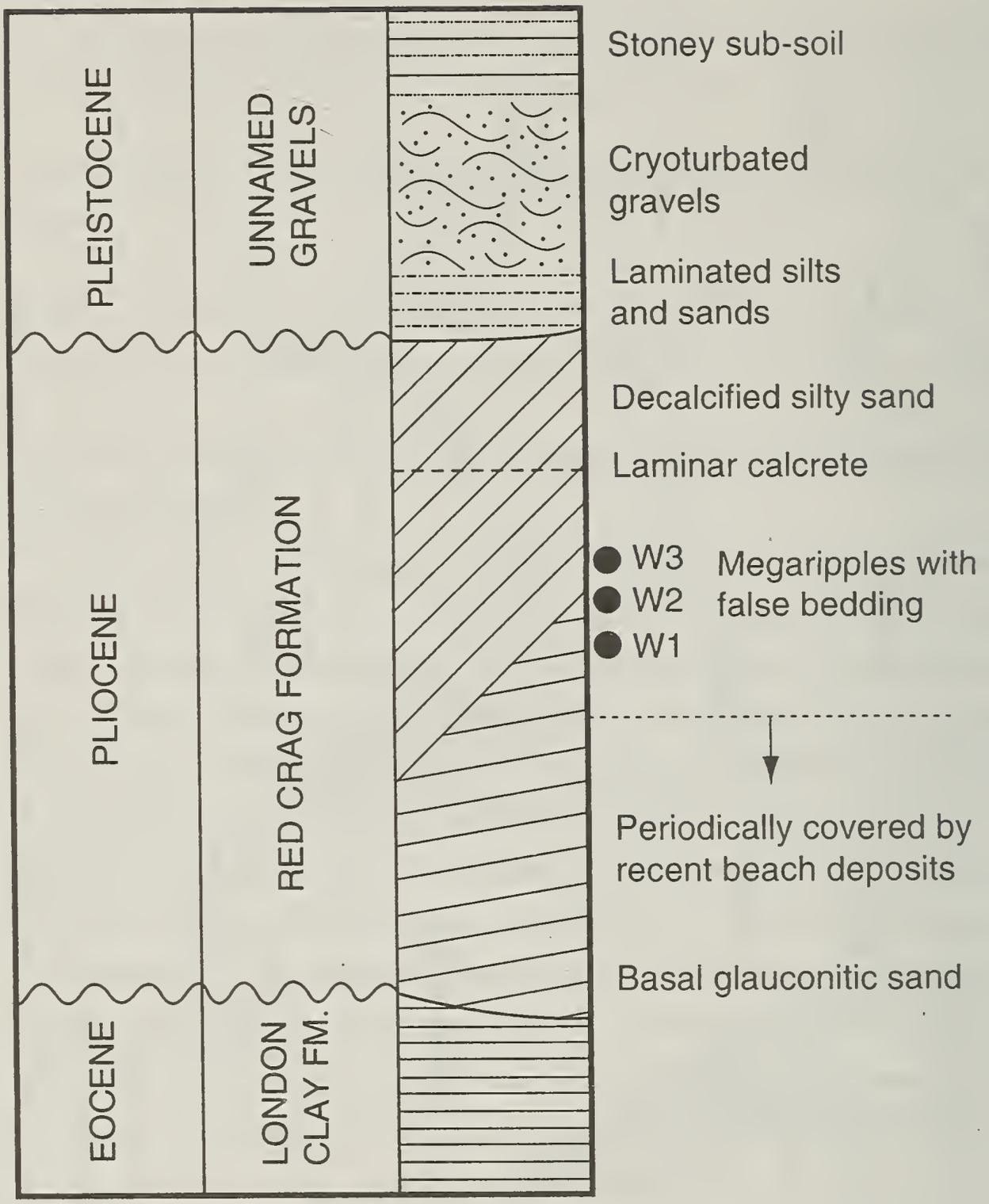

Fig. 2. Generalised stratigraphical section of the Naze Cliff (adapted after Hunt, 1989), showing major sedimentary structures and sampling horizons (W1-W3).

concentrated on the younger and more expansive Butleyan and Newbournian crags (*sensu* Harmer, 1900a, b) to the north.

Although Wood S.V. Snr (1866, 1872) recognised the unique nature of the molluscan fauna from the Red crags of Suffolk and Essex, the most celebrated biostratigraphical scheme was presented by the distinguished palaeontologist F.W. Harmer (1896, 1900a, 1900b, 1902; critically summarised in Boswell, 1952). His investigation of five localities in Essex, that included the Naze Cliff at Walton, finally indicated the presence of a single analogous Waltonian type molluscan fauna, quite unlike those described from the younger Newbournian and Butleyan stages of Suffolk. Harmer believed that the number of extinct thermophilic species decreased, in a linear manner, from the Waltonian to the Butleyan Stage. However, subsequent pollen (West, 1961), foraminiferal (Funnell, 1983; 1987) and ostracod (Wood *et al.*, 1994) analyses of the Red Crag indicate a more complex, cyclic, progression.

The North Atlantic partial range of *Neogloboquadrina atlantica*, which occurs throughout the Pre-Ludhamian pollen Stage of Norfolk (Beck *et al.*, 1972), indicates a late Pliocene age of between 3.2-2.4 myr BP for the Red Crag Formation (Funnell, 1987). A Pre-Ludhamian spectrum was described from the Red Crag Formation at Sizewell and this assemblage was found to equate with those described from the Walton Crag (Funnell and West, 1977). An expansive review of the biostratigraphical significance of the Walton Crag ostracods is given by Wood (in press).

SYSTEMATIC DESCRIPTIONS

Abbreviations used in both the synonymies and plate descriptions are: ALV-F Adult left valve, female. ARV-M Adult right valve, male. Acp Adult carapace, A-*n* juvenile stage. Material is either deposited in the Adrian Wood collection of the Micropalaeontological Museum, Institute of Earth Studies, Aberystwyth with catalogue numbers AMW/WALT/no or the Natural History Museum, London, with prefix catalogue numbers SO. All sizes are given in microns (μm). W1-W3 refer to the sample number; see Figs. 1 and 2 for their precise location.

Subclass Ostracoda Latreille, 1806

Order Podocopida G.W. Müller, 1894

Suborder Podocopina Sars, 1866

Superfamily Cytheracea Baird, 1850

Family Hemicytheridae Puri, 1953

Subfamily Aurilinae Puri, 1953

Genus *Aurila* Pokorny, 1955

Type species: *Cythere convexa* Baird, 1850

Aurila sherborni Wood *et al.*, 1992 (Pl. 1, Fig. 1)

1992 *Aurila sherborni* Wood *et al*: 213-214, pl. 2, figs 1-10.

Diagnosis. A large, punctate species of Aurila with a well developed smooth, elongate subovate eye tubercle and a swollen, L-shaped (in LV), opaque patch which surrounds the central muscle scars and continues dorsally in a band towards the hinge area.

Material.

W1	1v	-	W2	1v	-	W3	1v	-

Remarks. A rare species easily distinguished from other Pliocene Aurilid species by its large size, elongate carapace and the *littera*-shape of its opaque patch.

Aurila strongyla Wouters, 1973 (Pl. 1, Figs 2 & 3)

1857 *Cythere punctata* v. Münster; Jones: 24-25, pl. 2, figs 5a-d, 5f-h (*non* pl. 2, fig. 5e = *Loxoconcha pararhomboidea* Whatley and Maybury, 1988) (*non* Münster, 1830).

1870 *Cythere punctata* v. Münster; Jones: 156 (*non* Münster, 1830).

1878 *Cythere cicatricosa* (Reuss); Brady: 387-388, pl. 64 figs 3a-d (*non* Reuss, 1850)

1889 *Cythere convexa* Baird; Jones and Sherborn: 19 (*non* Baird, 1850)

1973 *Aurila strongyla* Wouters: 195-197, pl. 1, figs 1a-f, pl. 2, figs 1a-d.

1980 *Aurila convexa* (Baird); Wilkinson: pl. 1, figs 9-11 (*non* Baird, 1850).

Diagnosis (after Wouters, 1973). A species of the genus *Aurila* characterised by a convex ventral margin; weakly developed caudal process, situated at mid-height; surface of valve extremely punctate.

Material.

W1	6v	9cp	W2	6v	16cp	W3	6v	11cp

Remarks. This species differs from the type *Aurila convexa* (Baird, 1850) in being subquadrate rather than subtriangular in lateral view, possessing a substantial concavity of the ventral margin behind mid-length and a straight to weakly convex dorsal margin in the RV.

Aurila trigonula (Jones, 1857) (Pl. 1, Fig. 4)

1857 *Cythere trigonula* Jones: 25, pl. 3, figs 1a-h.

1870 *Cythere trigonula* Jones: 158.

1889 *Cythere trigonula* Jones; Jones and Sherborn: 19.

non 1955 *Hemicythere trigonula* (Jones); Oertli and Keij: 125, pl. 18, figs 9-10.

non 1957 *Aurila trigonula* (Jones); Van den Bold: 239, pl. 4, fig. 8.

non 1959 *Aurila trigonula* (Jones); Moyes: 35-36, pl. 11, fig. 2.

1980 *Aurila trigonula* (Jones); Wilkinson: pl. 1, figs 12-15.

Diagnosis. Large species of *Aurila*; dimorphic, males more elongate. RV subtriangular in dorsal view, carapace triangular in anterior or posterior view. LV higher, subquadrate to subovate. Dorsal and ventral margins angular, arcuate with apexes anterior and posterior of mid length, respectively. Caudal process well developed, situated ventrally. Valves ornamented with small, ovate fossae, inflated muri developed submarginal to the anterior. Prominent ventrolateral ridge; eye tubercle low and indistinct.

Material.

W1	4v	-	W2	6v	1cp	W3	15v	2cp

Remarks. An unpublished *Aurila* species (Harrison, 1977 MS) from the Redonian (Pliocene) of Brittany, similar to *A. trigonula*, however, the former species can be easily distinguished as it possess a low subcentral tubercle and deeply set fossae. *Aurila trigonula* is an important index species for the 'mid' Pliocene East Anglian crags and Oosterhout Formation of Holland (Wood, 1993 MS) where it is restricted to the upper levels of the *Thaerocythere oedichilus* - *T. wittei* - *Muellerina pliocenica* Acme Zone (Wood and Whatley, in press b).

Genus *Muellerina* Bassiouni, 1965

Type species: *Cythere latimarginata* Speyer, 1863

Muellerina lacunosa (Jones, 1857) (Pl. 1, Fig. 5)

1857 *Cythere lacunosa* Jones: 31, pl. 3, figs 5a-b.

1870 *Cythere sublacunosa* Jones; 156 (*nom. nov. pro Cythere lacunosa* Jones, 1857; *non Cytherina lacunosa* Reuss, 1850)

1889 *Cythere sublacunosa* Jones and Sherborn; 27.

1979 *Muellerina lacunosa* (Jones); Wouters: 228-229, pl. 2, fig. 2b (*non* pl. 2, figs 2a and 2c = *Muellerina orygyma* Wood and Whatley, in press a)

1980 *Murrayina lacunosa* (Jones); Wilkinson: pl. 2, fig. 14 (*non* pl. 2, fig. 12 = *Muellerina pliocenica* Wood and Whatley, in press a)

1988 *Muellerina lacunosa* (Jones); Lord, Horne and Robinson.: 4.

non 1989 *Muellerina lacunosa* (Jones); Horne and Kerr: pl. 2, fig. d (= *Muellerina pliocenica* Wood and Whatley, in press a).

in press a *Muellerina lacunosa* (Jones); Wood and Whatley: pl. 1, figs 4-6.

Diagnosis. A species of *Muellerina* with numerous, though rarely coalesced, subcircular fossae set within an undulose network of muri, concentrically arranged around a well developed subcentral tubercle. Weakly developed posteroventral and posterodorsal tubercles. Indistinct, plicate, ridge runs from the subcentral tubercle posterodorsally. In dorsal view, convex to straight truncation of the posterior submargin. Marginal radial pore canals numerous, 14-16 anteriorly, 4-6 posteriorly, straight/sinuous.

Material.

W1 - · 1cp	W2 2v -	W3 4v -

Remarks. Together with *Thaerocythere trachypora* (Jones, 1857), *Muellerina lacunosa* represents an important biostratigraphical marker species for the early to 'mid' Pliocene of the southern North Sea (*T. trachypora - M. lacunosa* Total Range Zone). It is thought to have evolved in the earliest Pliocene from the Miocene species *Muellerina parvipunctata* Uffernorde, 1981 (Wood and Whatley, in press a), while its last recorded occurrence appears to be intrinsically linked to the onset of major northern hemisphere glaciations at *ca*. 2.4 Ma.

Muellerina metabyssicola Wood and Whatley, in press a (Pl. 1, Fig. 6)

in press a *Muellerina metabyssicola* Wood and Whatley: pl. 1, figs 10 and 11.

Diagnosis. Carapace elongate, subquadrate/trapeziform. Dorsal margin concave with prominent raised anterior cardinal angle, dorsal convex. Listric truncation of posterior margin in dorsal view. Conspicuous subcentral, posterodorsal and posteroventral tubercles. Two further tubercles positioned in the dorsomedian and posteromedian regions connected by a conspicuous, sinuous, ridge. Second, finer ridge connecting subcentral and posterodorsal tubercles.

Material.

W1	2v	-	W2	1v	-	W3	1v	-

Remarks. Considered by Wood and Whatley (in press a) to represent an intermediate stage within the "*abyssicola*" lineage in which *M. praeabyssicola* and M. *abyssicola* constitute morphological end members.

Muellerina pliocenica Wood and Whatley, in press a (Pl. 1, Fig. 7)

1980 *Murrayina lacunosa* (Jones); Wilkinson: pl. 2., fig. 13 (*non* Jones, 1857)
1989 *Muellerina lacunosa* (Jones); Horne and Kerr: pl. 2 fig. d (*non* Jones, 1857)
1989 *Muellerina* sp. cf. *M. lacunosa* (Jones); Fourniguet *et al.*: pl. 1, fig. 19.
in press a *Muellerina pliocenica* Wood and Whatley: pl. 2, figs 2 and 4.

Diagnosis. Carapace elongate, subovate. Heavily denticulated, lipped, extension of the anterior margin. Fossae, cellate, irregularly disposed. Posterior dominated by three tubercles situated in the posterodorsal, posteroventral (this swelling continues anteriorly as a strong plicate ridge) and posteromedian fields, interconnected with expanded, undulose, sinuous muri.

Material.

W1	2v	-	W2	1v	-	W3	2v	-

Remarks. A Pliocene ostracod species with the rare distinction of having been recorded from both the east and west sides of the then British. peninsular. This species has been recorded from the crag deposits of the southern North Sea, Redonian (Upper Pliocene) of N.W. France, St. Erth Beds of Cornwall (Fourniguet *et al.*, 1989) and the Knocknasillage Member, County Wexford, Ireland (Horne & Kerr, 1989).

Subfamily Campylocytherinae Puri, 1960

Genus *Triginglymus* Blake, 1950 (=*Bensocythere* Hazel, 1967)

Type species: *Triginglymus hyperochus* Blake, 1950

Triginglymus sp. cf. *Cythere petrosa* Brady, 1878 (Pl. 1, Figs 8 & 9)

1980 *Cytheretta woodiana* (Jones); Wilkinson: pl. 2, figs 9-10.

Diagnosis. Carapace elongate ovate. Posterodorsal margin weakly concave, forming weak posteroventral caudal process, anterior obliquely rounded. Ventral and dorsal margins straight and parallel. Dimorphic, males more elongate Ornament pitted/reticulate, with deep, subrounded to elongate ovate fossae, coalescing in the subanterior region parallel to margin. Fossae separated by broad excavate muri. Weakly developed subcentral tubercle. Apparently blind.

Material.

W1	-	-	W2	-	-	W3	3v	-

Remarks. This species differs from its Miocene counterpart *Triginglymus petrosa* (Brady, 1878) as it is more elongate and posteriorly less swollen. Both *T.* sp. cf. *petrosa* and *T. dictyosigma* (Jones, 1857) occur, albeit rarely together, in the Coralline Crag Formation, however, the latter species can be distinguished by its greater height, more deeply excavated fossae and narrower, plicate, muri.

Family Thaerocytheridae Hazel, 1967

Subfamily Thaerocytherinae Hazel, 1967

Genus *Thaerocythere* Hazel, 1967

Type species: *Cythereis cremulata* Sars, 1866

Thaerocythere ?oedichilus (Brady, 1878) (Pl. 1, Fig. 10)

1878 *Cythere oedichilus* Brady: 388, pl. 64, fig. d 1a-d.

1967 *Thaerocythere*? *oedichilus* (Brady); Hazel: 25 and 26.

1991 *Thaerocythere* (*Thaerocythere?*) gr. *oedichilus* (Brady); Liebau: 158, fig. 84, pl. 90, figs 1-4. (?*non* Brady, 1878)

in press a *Thaerocythere oedichilus* (Brady); Wood and Whatley: pl. 2, figs 10-11 (?*non* Brady, 1878).

Diagnosis. Carapace, robust, subquadrate. Anterior obliquely rounded with broad denticulated marginal rim; posterior, angular, subtruncate. Dorsal margin weakly convex, ventral sinuous, converging posteriorly. Reticulation intricate, labyrinthine network of elongate/ovate cellate fossae. Muri inflated and raised either side of overgrown subcentral tubercle. Subventral ridge with alate posteroventral termination. Simple intermural and conjunctive pores common.

Material.

W1	1v	-	W2	3v	-	W3	3v	7cp

Remarks. *Cythere oedichilus* was originally described by Brady from the 'Antwerp Crag' (Miocene to early Pliocene) of Belgium; a species characterised by its broadly ovate outline in posterior view, swollen margins and a large, smooth, rounded subcentral tubercle. Although the Pliocene species *Thaerocythere oedichilus* (Brady) *sensu* Wood and Whatley (in press a) is synonymous with Pliocene/Pleistocene species *T.*(*T.*?) gr *oedichilus* (Brady,

1879 [sic]) *sensu* Liebau, 1991 it does not equate with *Cythere oedichilus* Brady, 1878 *sensu stricto*. *Thaerocythere oedichilus* (Brady) *sensu* Wood and Whatley (in press a) is subtriangular in posterior view, has smooth and flat submarginal regions, weak subcentral tubercle and is sculptured with an irregular, labyrinthine network of elongate cellate fossae rather than, "rounded pittings, which are arranged in transverse rows" (Brady, 1878 p. 388).

In addition, 13 specimens of *Thaerocythere ?oedichilus* (Brady) *sensu* Wouters (1978 MS, p.200-200, pl.23, figs 5a-5b; pl. 42, fig. 6) were collected from the late Miocene, Duerne Sands, of Belgium by Wouters. His figured specimens appear to be worn juveniles of a *Thaerocythere* species quite different from Wood and Whatley (in press a) and more closely allied to the *Cythere oedichilus* Brady *sensu stricto.*

Thaerocythere oedichilus sensu Wood and Whatley (in press a - ?*non* Brady) may represent a new thaerocytherinid species, however, examination of Brady's type material is required before further taxonomic clarification can be made.

Thaerocythere trachypora (Jones, 1857) (Pl. 1, Fig. 11; Pl. 2, Fig. 1)

1857 *Cythere trachypora* Jones: 36, pl. 3, figs 9f-i.

1870 *Cythere trachypora* Jones; Jones: 156.

non 1889 *Cythere trachypora* Jones; Jones and Sherborn: 24, pl. 3, figs 9a-9b (= *Thaerocythere mayburyae* Cronin, 1991)

1980 *Quadracythere macropora* (Bosquet); Wilkinson: pl. 2, figs 16-17 (*non* Bosquet, 1852)

? 1981 "*Quadracythere*" *ruspelensis* Uffenorde, pl. 7, fig. 21.

? 1988 *Thaerocythere* sp. Lord, Horne and Robinson; 4.

? 1991 *Thaerocythere whatleyi* Cronin; 780, pl. 10, figs 11-12 and 14.

in press a *Thaerocythere trachypora* (Jones); Wood and Whatley: pl. 3, fig. 1.

Diagnosis. Robust, quadrate, species of *Thaerocythere* with raised anterior cardinal angle in LV, dorsal margin sinuous with concavity at mid length. Ornament composed of equally well developed radial and concentric muri arranged about a solid subcentral tubercle. Muri angled, above mid-length, from posterior cardinal angle to mid height at the anterior

margin. Fossae subquadrate, pore-conuli common and central on solum, intermural and conjunctive pores rare.

Material.

W1	3v	-	W2	6v	3cp	W3	3v	2cp

Remarks. One of four species originally described by Jones (1857) from the Walton Crag and in conjunction with *Muellerina lacunosa* it is an important and common marker species for the early to 'mid' Pliocene of the southern North Sea Basin.

Thaerocythere wittei Wood and Whatley, in press a (Pl. 2, Fig. 2)

1991 *Thaerocythere* (*Thaerocythere*) sp. LA58 Liebau: 158, pl. 90, fig. 5.
in press a *Thaerocythere wittei* Wood and Whatley: pl. 3, fig. 10.

Diagnosis. Carapace elongate rectangular with sub-parallel dorsal and ventral margins. Marked concavity of posterodorsal margin resulting in a sub-triangular posterior extremity. Surface pitted with moderately large, deep, subcircular to slit-like cellate fossae, coalescing posteriorly, radially disposed about high subcentral tubercle.

Material.

W1	5v	2cp	W2	3v	-	W3	6v	-

Remarks. This species was first figured by Liebau (1991) using specimens collected from the Plio-Pleistocene of the 'Antwerp Crag', Belgium. *Thaerocythere wittei* is, however, a important index species for the early-'mid' Pliocene of The Netherlands and if one adopts the ostracod based biostratigraphical framework of Wood and Whatley (in press b) it is more likely that Liebau's specimens were recovered from the 'mid' Pliocene, Lillo Formation rather than from Pleistocene strata.

Thaerocythere epistylium sp. nov. (Pl. 2, Figs 3 & 4)

in press a *Thaerocythere* sp. A Wood and Whatley: pl. 3, fig. 14.

Derivation of name. Greek, *επιστψλιον - epistylion* = a cross beam over; pertaining to the pronounced submarginal murus that connects the anterior and posterior cardinal angles.

Diagnosis. Elongate ovate/subquadrate in lateral view. Well developed anterodorsal-posterodorsal ridge terminating posteriorly at mid-height on the submargin. This peripheral structure is connected to the subcentral tubercle *via* a plicate ridge attached to the posterior cardinal angle. The muri within the dorsomedian field parallel this obliquely angled ridge.

Distribution. Coralline Crag Formation at Sutton Knoll and Orford, and the Walton Crag at Walton on-the-Naze.

Type locality and horizon. Sutton Knoll, sample S4, Coralline Crag Formation, Pliocene, East Anglia.

Material.

W1	1v	-	W2	2v	-	W3	-	-

Including 7 valves from the Coralline Crag Formation from which the types are taken.

Dimensions of Types.				**L**	**H**
Holotype	ARV	OS 14856	Sutton Knoll(S4)	780	380
Paratype	RV?A-1	OS 14857	Sutton Knoll(S3)	700	380
Paratype	LVA-1	OS 14858	Sutton Knoll(S3)	610	360

Description. Carapace quadrate in lateral view, dorsal margin straight to slightly convex, ventral sinuous with convexity behind mid-length. Anterior obliquely rounded with weakly denticulate, narrow, fragile rim; posterior subtruncate with concavity, prevalent in LV,

above mid-height. Maximum length ventral of mid-height, greatest width at subcentral tubercle. Eye tubercle, moderately large, conical and mounted on anterodorsal, submarginal, murus.

Radial component dominant in reticulum; strong, arcuate, plicate ridge connecting robust, punctate subcentral tubercle to submarginal murus at the posterior cardinal angle. Within the dorsal region other muri parallel this dominant, oblique ridge. Subperipheral murus most strongly developed in the anterodorsal and dorsal fields. Two sub-parallel, longitudinal, muri developed in the anteromedian field, projecting forward from the subcentral tubercle to the anterior submargin. Posterior, bifid, termination of the subventral ridge.

Remarks. Both this species and *Thaerocythere mayburyae* Cronin possess a well developed dorsomarginal ridge with mounted eye, however, the latter species has a higher lenght:height ratio and lacks the interconnecting posterodorsal ridge. The concentric and radial components of the reticulation are equally well developed in *T. mayburyae*. Both the size and lateral shape of *T. trachypora* equates well with this species, however, its margins are less angular and it lacks the elevated anterodorsal-dorsal murus.

Family Leptocytheridae Hanai, 1957

Genus *Leptocythere* Sars, 1925

Type species: *Cythere pellucida* Baird, 1850

Leptocythere recurata (Jones and Sherborn, 1887) (Pl. 2, Fig. 5)

1878 ?*Cythere cribrosa* Brady: 384, pl. 64, figs 4a-4d (*non* Brady, Crosskey and Robertson, 1874)

1887 *Cythere recurata* Jones and Sherborn: 388.

1889 *Cythere recurata* Jones and Sherborn; Jones and Sherborn: 21, pl. 1, fig. 1.

1981 *Leptocythere* (*Leptocythere*) sp. Uffenorde; 135, pl. 4, fig. 16.

cf. 1984 *Leptocythere* sp. West *et al.*: pl.1, fig. 5d.

cf. 1989 *Leptocythere* sp.A Horne and Kerr; pl. 1 figs c-e.

Diagnosis. Carapace medium size (550-650 μm long), robust, elongate-subquadrate. Dimorphic, male more elongate and less high. Dorsal margin evenly arcuate; anterior obliquely rounded, posterior subtruncate. Maximum length at mid-height, greatest height at anterior cardinal angle. Reticulate ornament comprising concentrically disposed, ovate to subcircular, deep fossae and smooth rounded muri, commonly subdued in the posteromedian field. Eye tubercle moderately well developed, subrectangular; post-ocular and dorsomedian sulci distinct, posteroventral alar protuberance, variable, weak to fortified.

Material.

W1	-	-	W2	1v	1cp	W3	1v	1cp

Remarks. *Leptocythere recurata* has on occasion been synonymized with *L. cribrosa* (Brady *et al.*, 1874), however, the latter species has a distinctively ovate posterior margin, less quadrate outline in dorsal view and weak post-ocular and dorsomedian sulci. *Leptocythere* sp. A Horne and Kerr and *L.* sp. West *et al.* are placed in questionable synonymy as both are considerably smaller than *L. recurata* (460-500 m long) and exhibit a high degree of mural excavation which has literally undermined the reticulum in the posteroventral field.

Family Cytherideidae Sars, 1925

Subfamily Cytherideinae Sars, 1925

Genus *Cytheridea* Bosquet, 1852

Type species: *Cythere muelleri* v. Munster, 1930

Cytheridea sp. cf. *C. mülleri mülleri* (v. Münster, 1830) (Pl. 2, Fig. 6 to 8)

Diagnosis. Carapace subquadrate in dorsal view; subtrapezoidal in lateral view, anterior denticulate and obliquely rounded; posterior truncated, posteroventral margin narrowly rounded. Dorsal and posteroventral margins convex. Surface of valves pitted. Broad, faint, riblets developed subparallel to the anterior margin. Vestibulate.

Material.

W1	-	-	W2	1v	-	W3	2v	-

Remarks. Although the lateral outline of *Cytheridea mülleri mülleri* (v. Münster) is very similar to this species, the type species generally possesses 15 anterior marginal denticules on its RV and 7 on the LV, while only 10 have been counted on both valves of the present species. In addition *C. mülleri mülleri* has a heavily pitted exterior with a number of distinct anterior ribs.

The lateral outline of this species also resembles *Cytheridea hoerstgenensis* Bassiouni, 1962, a species recorded from the Miocene of North-West Europe (Wouters, 1978 MS; Wood, 1993 MS). However, *Cytheridea hoerstgenensis* can be easily distinguished as it is much higher with a pronounced dorsal convexity; possesses 12-14 anterior marginal denticles, and as with *Cytheridea* sp. A the anteromedian field is cut by a number of 'stepped ridges'. The latter criteria can be used to distinguish the two Walton Crag species *Cytheridea* sp. A from *C.* sp. cf. *mülleri mülleri*.

Cytheridea sp. A (Pl. 2, Fig. 9)

1878 *Cytheridea mülleri* (Münster); Brady: 397-398, pl. 62, figs 4a-4c (*non* Münster, 1830).

1918 *Cytheridea mülleri* (Münster); Kuiper: 28-31, pl. 1, fig. 9 (*non* Münster, 1830).

1962 *Cytheridea paracuminata paracuminata* Kollmann; Bassiouni: 13-14, pl. 1, figs 5-7 (*non* Kollmann, 1960).

1981 *Cytheridea* sp. 3 Uffenorde: 139, pl. 4, fig. 23; pl. 5, figs 3-4.

Diagnosis. Sexual dimorphism pronounced, males more elongate and in dorsal view narrower than females. Carapace ovate in dorsal view; in lateral view subtrapezoidal, anterior obliquely rounded, posterior obliquely truncated and narrowly rounded posteroventrally. Dorsal margin straight to slight convex, ventral margin anteriorly convex-posteriorly concave. Reticulate, numerous subcircular primary and secondary pits, former arranged in four rows subparallel to the anterior margin. Four submarginal, sinuous, 'step'-like, ridges running from the anterior to the posterior cardinal angles. The anterior and posterior margins bear 7 and 3 pointed denticles respectively.

Material.

W1	2v	-	W2	1v	-	W3	2v	-

Remarks. *Cytheridea* sp. A is similar in many respects to the Upper Miocene species *Cytheridea pernota* Oertli and Keij, 1955, however, the former has a quite distinct posterior cardinal angle and can be distinguished by its much finer pitting and characteristic stepped, submarginal, ridgelets. This species has also been described by Wouters (1978 MS, as *Cytheridea amphisparsa nom. nud.*) from Belgian marine sediments of Middle Miocene (Edegem Sands) to 'mid' Pliocene (Oorderen Sands) age. Wood (1993 MS) also recorded this species, in great numbers, from the Oosterhout Formation (FC1 Foraminifera Zone Doppert, 1980 = *Thaerocythere woutersi* - *T. biformis* Total Range Zone Wood and Whatley, in press b) where it occurs commonly with *C. hoerstgenensis* Bassiouni, 1962. This latter species is, however, quite distinct as it possesses 12 anterior marginal denticles rather than 7.

Genus *Cyprideis* Jones, 1857

Type species: *Candona torosa* Jones, 1850

Cyprideis sp. (Pl. 2, Fig. 10)

Diagnosis. Single robust ?female carapace, subovate-subquadrate in lateral view, ventral margin straight; inflated posteroventrally. Anterior and posterior obliquely rounded. Valve apparently smooth though finer reticulation is obscured by feroxyhitic precipitate. Dorsomedian sulcus weak; posteroventral spine apparently absent.

Material.

W1	1v	-	W2	-	-	W3	-	-

Remarks. This Pliocene species differs from the type *Cyprideis torosa* (Jones, 1850) by having a 'box'-like outline in lateral view, straight ventral margin and distinct posterior cardinal angle in the RV.

Genus *Haplocytheridea* Stephenson, 1941 (= *Sarsicytheridea* Athersuch, 1982)

Type species: *Haplocytheridea montgomeryensis* Howe and Chambers, 1935

Haplocytheridea pinguis (Jones, 1857) (Pl. 2, Fig. 11)

partim 1857 *Cythere* (*Cytheridea*) *pinguis* Jones: 43; pl. 2, figs 4b-c, e-f (*non* pl. 2, fig. 4d = *Cytheretta harmeri* Wilkinson, 1980).

1870 *Cythere* (*Cytheridea*) *pinguis* Jones; Jones: 158.

non 1878 *Cytheridea pinguis* (Jones); Brady, 397, pl. 64, figs 3a-3d (? = *Cytheridea lienenklausi* Kuiper, 1918) (*non* Jones, 1857).

non 1887 *Cytheridea pinguis* (Jones); Jones: 455 (= *Cytheridea punctillata* Brady, 1865).

non 1980 *Haplocytheridea pinguis* (Jones); Wilkinson: pl. 1, fig. 5 (= *Haplocytheridea robusta* Wood *et al.*, 1992)

partim 1988 ?*Haplocytheridea pinguis* (Jones); Lord, Horne and Robinson: 4.

1992 *Haplocytheridea pinguis* (Jones); Wood *et al.*: pl. 1, figs 10-11.

Diagnosis. In dorsal view carapace elongate ovate, anterior with denticulate projecting lip in both valves. Greatest height behind mid-length. Dimorphic, males lower and more elongate. Subtrapezoidal to subquadrate in lateral view, anterior obliquely rounded; dorsal margin straight. Posterior narrowly rounded ventrally, projecting below weakly convex ventral margin. LV>RV, overlapping the RV along almost the entire periphery. Surface coarse with regular puncta in adults and penultimate instar, more irregularly disposed in juveniles. Anteriorly and posteriorly vestibulate.

Material.

W1	1v	-	W2	2v	-	W3	2v	1cp

Remarks. Juveniles of both *H. pinguis* and *H. robusta* have often been placed in synonymy. However, juveniles of the former species are notably less high and have puncta developed in the A-4 stage while such reticulation has only been observed in the penultimate stage of *H. robusta*.

Haplocytheridea robusta Wood *et al.*, 1992 (Pl. 3, Fig. 1)

1857 *Cythere* (*Cytheridea*) *pinguis* Jones: 43; pl. 2, fig. 4a .

1980 *Haplocytheridea pinguis* (Jones); Wilkinson: pl. 1, fig. 5.

1992 *Haplocytheridea robusta* (Jones); Wood *et al.*: 211-212, pl. 1, figs 1-9.

Diagnosis. Strongly calcified species of *Haplocytheridea*, length to height ratio lower than normal for the genus. RV subtriangular with arched dorsal margin, LV subquadrate with weakly developed anterior denticulation. Coarse, scattered puncta developed in adults.

Material.

W1	1v	-	W2	3v	-	W3	-	-

Remarks. This species differs from *Haplocytheridea pinguis* (Jones, 1857), in its lower L:H ratio, straight ventral margin and broadly rounded posterior in both valves.

Haplocytheridea sp. aff. *H. cypridoides* (Brady, 1878) (Pl. 3, Fig. 2)

Diagnosis. Elongate ovate species of *Haplocytheridea* with numerous, fine puncta, in the median-posteromedian region. Anterior rounded with fine lipped rim, *non* denticulate, posterior more produced, ovately rounded. Dorsal margin broadly convex, ventral sinuous with noticeable convexity in front of the mid length and posterior; greatest width well behind the mid-length.

Material.

W1	1v	-	W2	-	-	W3	1v	-

Remarks. The juveniles of this species have the tumidity and triangularity (in the RV) of *H. cypridoides* but the adults are distinctively more elongate-ovate to subquadrate with a prominent anterior cardinal angle (in LV). The disposition of puncta and the lateral outline of *Haplocytheridea lienenklausi* (Kuiper) is similar to *H.* sp. aff. *cypridoides*, although the presence of broad and relatively flat anterior and posterior submargins (associated with the flamboyant lip structures of this species) is quite distinctive.

Despite occurring in both the Walton Red Crag and Coralline Crag formations, this species had attained its peak abundance during the Upper Miocene, *Thaerocythere woutersi* - *Thaerocythere biformis* Total Range Zone (Wood & Whatley, in press b).

Family Loxoconchidae Sars, 1866

Subfamily Loxoconchinae Sars, 1925

Genus *Cytheromorpha* Hirschmann, 1909

Type species: *Cythere fuscata* Brady, 1869 (=*Cytheromorpha albula* Hirschmann, 1909)

Cytheromorpha sp. A (Pl. 3, Figs 3 to 4)

1988 ?*Bonnyannella exigua* (Wouters, 1978 *nom. nud.*); Lord, Horne and Robinson: 4.

1989 *Bonnyannella* sp. Horne and Kerr: pl. 2, figs e-f.

Diagnosis. Carapace elongate subquadrate to subreniform in lateral view; anterior broadly rounded with thin marginal rim, dorsal and ventral margins converge posteriorly towards narrower ovately-rounded posterior with flattened submarginal field. Greatest width behind mid-length. Dimorphic, male more elongate than female. Regularly pitted, weak posteroventral alar protuberance continuing as a raised murum to mid-height on the posterior margin. Well developed eye tubercle situated in front of the anterior cardinal angle and two weak, circular, nodes situated in the dorsomedian field. Hinge gongylodont, median element smooth, posterior tooth of right valve arcuate and lobed.

Material.

W1	-	-	W2	1v	-	W3	1v	-

Remarks. This species has previously been mis-identified and commonly placed in synonymy with *Cytheromorpha exigua* Wouters, 1978 MS *nom. nud.*, from the Middle Miocene of Belgium. Although both species clearly belong to the genus *Cytheromorpha*, the Miocene species, *C. exigua* is comparatively stout, subquadrate in lateral view and coarsely punctate.

Photographic examination of the type species *Pteroloxa venipuncta* Swain, 1963, from the Gubik Formation of Alaska, and *Bonneyannella* Athersuch, 1982 clearly show them both to be junior synonyms of *Cytheromorpha* Hirschmann, 1909. *Roundstonia*

Neale, 1973, which includes the species *R. globulifera* (Brady, 1868); *R. minima* Whatley and Maybury, 1986 and *R. magna* Maybury and Whatley, 1986; although possessing pronounced lateral nodes, have similar carapace outlines, hingement (gongylodont with slight variation in the curvature of the posterior tooth in the RV) and central muscle scar patterns as *Cytheromorpha*. In my opinion *Roundstonia* is also a junior synonym of *Cytheromorpha*.

Family Neocytherideidae Puri, 1957

Subfamily Neocytherideidinae Puri, 1957

Genus *Pontocythere* Dubowski, 1939

Type species: *Pontocythere tchernjawskii*, 1939

Pontocythere botellina (Jones, 1870) (Pl. 3, Figs 5 to 6)

1857 *Cythere* (*Cytherideis*) *flavida* Müller; Jones: 50-51, pl. 4, figs 4a-4c (*non* Müller, 1785).

1870 *Cythere* (*Cytherideis*) *botellina* Jones: 157 and 158.

1889 *Cytherideis botellina* (Jones); Jones and Sherborn: 45.

1980 *Cushmanidea lithodomoides* (Bosquet); Wilkinson: pl. 1, figs 7-8 (*non* Bosquet, 1852).

1988 *Pontocythere lithodomoides* (Bosquet); Lord, Horne and Robinson: 4 (*non* Bosquet, 1852).

Diagnosis. A large species of *Pontocythere* which exhibits pronounced sexual dimorphism, males attenuated and less high. Dorsal margin arched about a angular apex situated behind the mid length. Surface both punctate and reticulate; normal and sieve pores common. Surface ornamented with low amplitude ripples orientated obliquely to the ventral margin, subparallel to the anterior.

Material

W1	10v	6cp	W2	9v	2cp	W3	7v	2cp

Remarks. *Pontocythere lithodomoides* (Bosquet, 1852), the probable Miocene ancestor of this species (*op. cit.* Wouters, 1979), can been distinguished by its rounded dorsal extremity, narrower posterior margin in LV and ribbed reticulation that parallels the ventral margin rather than being set oblique to it as in *P. botellina*.

Pontocythere sp. cf. *P. elongata* (Brady, 1868) (Pl. 3, Fig. 7)

Diagnosis. (from single juvenile moult) Carapace large, moderately elongate, cylindriform; anterior obliquely rounded, posterior ovately rounded to subtruncate; greatest height behind mid-length. Valve reticulate with fine ripples, anteriorly pronounced (finer structures obscured by precipitate).

Material.

W1	1v	-	W2	-	-	W3	-	-

Remarks. This species differs from juveniles of *P. botellina* in being individually higher and less tapered posteriorly. Analysis of *P. elongata* juveniles, from the eastern shelf of the N.E. Atlantic, clearly showed them to be less arcuate dorsally and obliquely rounded rather than subtruncate posteriorly.

Family Trachyleberididae Sylvester-Bradley, 1948

Subfamily Trachyleberidinae Sylvester-Bradley, 1948

Genus *Cletocythereis* Swain, 1963

Type species: *Cythere rastromarginata* Brady, 1880

Cletocythereis jonesi Wood *et al.*, 1992 (Pl. 3, Fig. 8)

1857 *Cythere macropora* Bosquet; Jones: 35, pl. 3, figs 9a-9e (*non* pl. 3, fig 9e = *Cythere lacunosa* Jones, 1857) (*non* Bosquet, 1852).

1870 *Cythere macropora* Bosquet; Jones: 158 (*non* Bosquet, 1852).

1887 *Cythereis hoernesi* (Speyer); Jones and Sherborn: 454 (*non* Speyer, 1863).

1889 *Cythereis hoernesi* (Speyer); Jones and Sherborn: 32-33, pl. 1 fig. 7 (*non* speyer, 1863).

1980 *Hermanites haidingeri haidingeri* (Reuss); Wilkinson: pl. 2, fig. 11 (*non* Reuss, 1850).

1988 *Hermanites haidingeri haidingeri* (Reuss) *sensu* Wilkinson, 1980; Lord, Horne and Robinson: 4 (*non* Reuss, 1850).

1992 *Cletocythereis jonesi* Wood *et al.*: 214, 216-217, pl. 2, figs 11-15; pl. 3, figs 1-12.

Diagnosis. A large sub-rectangular species of *Cletocythereis*, surface strongly reticulated with large, marginally linked, cellate fossae. Anterior marginal rim reticulate with a series of narrow transverse, elongate, cellate fossae. Two prominent dorsal and sub-alar ventrolateral ridges, the latter terminating in a complex loop posteroventrally. Characteristic anterodorsal expansion of the selvage, forming a small rim-tooth in the LV anterior of the anterior socket.

Material.

W1	10v	-	W2	8v	-	W3	9v	-

Remarks. This species was originally described from Sutton Knoll, Suffolk by Jones (1857), however, it has be encountered in great numbers from sequences of comparable age within the Dutch (Wood 1993 MS) and Belgium (Wouters *op. cit.* 1978 MS) Neogene successions. Wood and Whatley (in press b) recognised *C. jonesi* as an important accessory species in the 'mid' Pliocene, *Thaerocythere oedichilus - T. wittei - Muellerina*

pliocenica Acme Zone (= FB benthonic foraminifera zone of Doppert, 1980 and ostracod ecozones OPB and OPC, Wood *et al.*, 1994).

A remarkably similar species of has been identified from the Redonian (Upper Pliocene) of northern France (Maybury, 1985 MS).

Subfamily Cytherettinae Triebel, 1952

Genus *Cytheretta* G.W. Müller, 1894

Type species: *Cytherina subradiosa* Roemer, 1838 (=*Cytheretta rubra* G.W. Müller, 1894)

Cytheretta harmeri Wilkinson, 1980 (Pl. 3, Fig. 9)

pars 1857 *Cythere* (*Cytheridea*) *pinguis* Jones, pl. 2, fig 4b.
pars 1857 *Cythere woodiana* Jones, 29-30, pl. 3, figs 2d-2f.
1980 *Cytheretta harmeri* Wilkinson: 302-303, pl. 1, figs 1-3.
? 1988 ?*Cytheretta harmeri* Wilkinson; Lord, Horne and Robinson: 4.

Diagnosis. Finely crafted yet moderately robust carapace. Elongate subquadrate to subovate in dorsal view, laterally subovate. Anterior obliquely truncated, posterior subtruncate with concavity, prevalent in RV, above mid-height; dorsal and ventral margins sinuous and parallel. Ornament consists of 10-13 subparallel, longitudinal rows of coarse rounded pits disposed along the median region of both valves. Smooth in the anterodorsal field.

Material.

W1	1v	-	W2	-	-	W3	1v	-

Remarks. At present this species has only been described from the Pliocene of East Anglia and the Oorderen Sands, Lillo Formation of Belgium (in Wouters, 1978 MS as *pars Cytheretta sphaerulolineata*), however, it has a number of morphological allies from the Upper Tertiary of northern Europe. Both its carapace dimensions and lateral outline are

similar to *Cytheretta semipunctata* (Bornemann, 1855; redescribed by Weiss, 1983), this predominantly Oligocene species is, however, small and has only 6 longitudinal rows of puncta. Although similar in may other respects, the lateral outline of the Upper Miocene species *Cytheretta hiltermanni* Bassiouni, 1962 is quite clearly tapered towards its anterior, the posterior margin of this species is both more angular and narrower than in *C. harmeri*.

Cytheretta woodiana (Jones, 1857) (Pl. 3, Fig. 10)

1857 *Cythere woodiana* Jones: 29-30, pl. 3, figs 2a-2g.

1870 *Cythere woodiana* Jones; Jones: 158.

1878 *Cythere woodiana* Jones; Brady: 364, pl. 15, figs 4a-4b.

non 1980 *Cytheretta woodiana* (Jones); Wilkinson: pl. 2, figs 9-10 (=*Triginglymus* sp. cf. *Cythere petrosa* Brady, 1878 herein)

Diagnosis. A coarsely punctate species of *Cytheretta*, in which the puncta are arranged into 15-16 subparallel arcuate, longitudinal traverses which mirror the lateral outline of both valves; puncta becoming finer towards margin. Lip-like extension of the posteroventral margin. Moderately well developed eye tubercles.

Material.

W1	-	-	W2	1v	-	W3	-	-

Remarks. This species differs from its Pliocene Crag contemporary *Cytheretta harmeri* in having a greater length:height ratio and a truncate posterior margin with lipped extension posteroventrally.

Family Schizocytherinae Mandelstam, 1960

Genus *Schizocythere* Triebel, 1950

Type species: *Schizocythere hollandica* Triebel, 1950

Schizocythere pliocenica Wilkinson, 1980 (Pl. 3, Fig. 11)

1980 *Schizocythere pliocenica* Wilkinson, 1980: pl. 2, figs 7-8.

Diagnosis. Quadrate in lateral view, anterior obliquely rounded, posterior subtruncate; ventral and dorsal margins sinuous and parallel. Reticulation, composed of two, submarginal ventral and anterior ribs; short longitudinal ridge connecting ventromedian and central-anterior marginal region. Muri irregular often tumid especially dorsal of mid-height. Submarginal and irregular tuberculate swelling in front of posterior cardinal angle, connected to dorsal margin *via* short rib. Conspicuous, scattered, celate pores.

Material.

W1	-	-	W2	-	-	W3	1v	-

Remarks. The disposition of both submarginal and median ridges, and to a lesser extent the celate pores, are alike in *Schizocythere pliocenica* and the type species *S. hollandica* Triebel, 1950. Similarities in the form and disposition of both ridges and pores can be seen in Fig. 3. All four macroreticulation reconstructions are composite in nature and were generated from a number of specimens. At various ontogenetic stages the two species can be easily distinguished. At the A-2/3 stage the primary ribs, those submarginal to the anterior and ventral margins, are fragile, discontinuous and partially undercut in *S. hollandica* but plicate in *S. pliocenica*. At the A-1 stage the ridges on *S. hollandica* form a more continuous network in which the muri, dorsal of the mid-height, are also narrow, raised and undercut; in *S. pliocenica* they remain plicate. Intermediate forms have been figured by Wouters (1978 MS, pl. 35, fig. 1a) from the Middle Miocene, Zonderschot Sands, Belgium.

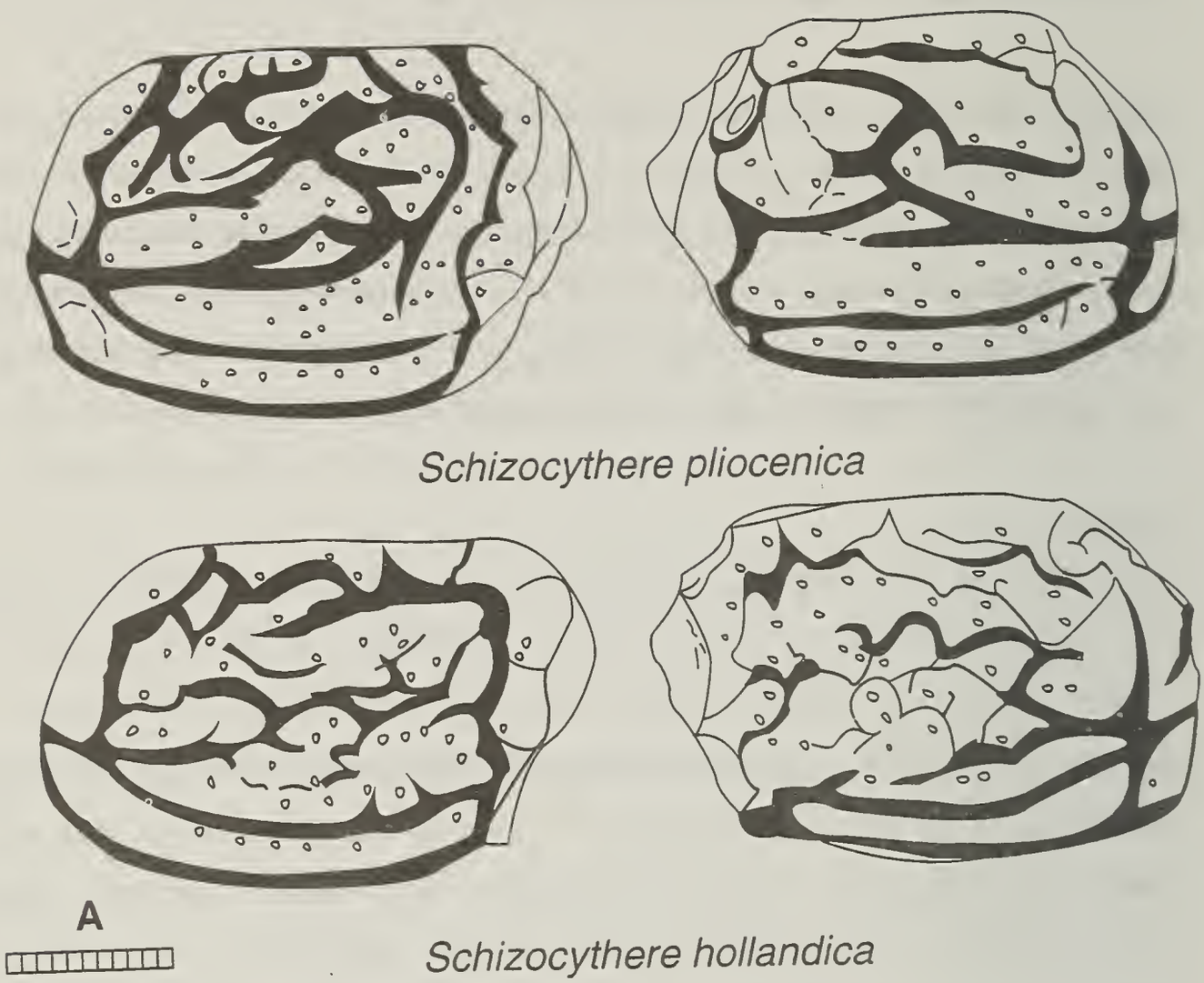

Fig. 3. Composite macrorecticulation reconstruction of the Neogene *Schizocythere* species, *S. pliocenica* Wilkinson, 1980 and *S. hollandica* Triebel, 1950. Scale bar A = 100µm.

DISCUSSION

The grain properties and sedimentary structures of the Pliocene section at Walton-on-the-Naze are indicative of a high energy sublittoral environment, not unlike like those observed off the East Anglian coast today (Dixon, 1979; Zalasiewicz and Mathers, 1985). Such energetic conditions of sedimentation may have altered the original ostracod bioceonesis of the Walton Crag, indeed, malacological evidence indicates that reworking and transportation of shells has occurred between the crags of East Anglia (Gibbard and Zalasiewicz, 1988).

Approximately 20% of the ostracod fauna collected from the younger Red crags (Newbourn and Butley) at Buckanaye Farm (Fig. 1) were derived from the Coralline Crag, and included such species as *A. strongyla, M. lacunosa* and *T. trachypora.* At present no Coralline Crag species have been found in the younger Chillesford Sand Member of the Norwich Crag Formation, Chillesford (Fig. 1). The number of reworked Coralline Crag specimens is extremely variable even at proximal sample sites such as Chillesford Church Pit and Buckanaye Farm. These discrepancies undoubtedly reflected very localised variations in the reworking of bedrock surface by water flow (Mathers and Zalasiewicz, 1988). However, one would expect the number of allocthonous specimens to be lower at the Naze Cliff, which is presently situated 25km south of the main Coralline Crag exposure.

The ontogenetic peculiarities of crustacea, most notably ecdysis, can allow one to determine whether the dominant species are representative of a true palaeobioceonesis by studying the distribution of their instars (Whatley, 1988). Although a high percentage of intact carapaces were discovered, further analysis of the preserved ontogenetic stages of *A. strongyla, A. trigonula* and *P. botellina* indicates that some disruption of the expected adult:juvenile ratios has occurred. The presence of the mesohaline genus *Cyprideis* suggests additional localised influxes of material.

Twenty five species of Ostracoda, all of which are presently thought to be extinct, were identified from the three Naze Cliff samples. As with other major fossil groups (Wood S.V. snr 1866; Harmer, 1900b), the Walton Crag ostracod assemblages closely resemble those of the Coralline Crag, and although the Coralline Crag ostracod faunas are more diverse (50-70 species per 1kg sample) they are also depauperate of extant species. This trend is clearly represented in Table 2, where the ostracod faunas of the younger Red

	Coralline Crag			Walton Crag			Newbourn Crag			Butley Crag			Norwich Crag		
Total number of species present	120			25			10			17			17		
Total number of extant species (%)	5 (4.2)			0 (0)			3 (30)			9 (52.9)			10 (58.8)		
Species Type	T	E	C	T	E	C	T	E	C	T	E	C	T	E	C
Number	0	5	0	0	0	0	0	0	3	0	4	5	0	5	5

Table 2. Ostracod diversity and faunal composition of the East Anglian Crags. T thermophilic species, E eurythermal species and C cryophilic species, denotes the thermal tolerance of the extant species present (thermal tolerances after Wood, 1993 MS).

Crag stages and the Norwich Crag Formation are dominated by extant cryophilic species. It was suggested by Wood *et al.*, (1994) that the Walton fauna represents the recolonization of expanding sub-littoral niches by a relatively low diversity, eurythermal, Coralline Crag remanie.

Wood S.V. snr (1866 and 1872) indicated that clear affinities existed between the molluscan faunas of the Coralline and Walton crags which distinguished them from the rest of the Red Crag. Harmer (1896) held a more progressive opinion and sought the separation of the "Walton beds" (*sensu lato*) from the Red Crag. Exactly a century later, the ostracodological evidence appears to support Harmers' view.

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REFERENCES

ATHERSUCH, J. 1982. On *Bonnyannella robertsoni* (Brady). *A Stereo-Atlas of Ostracod Shells*, **9**(14), 77-84.

BAIRD, W. 1850. Description of several new species of Entomostraca. *Annals of the Magazine of natural History*, series 2, **10**, 56-59.

BASSIOUNI, M.A. 1962. Ostracoden aus dem Mittelmiozän in NW Deutschland.*Roemeriana*, Clausthal-Zellerfellf, **3**, 1-99, 9pls.

BECK, R.B., FUNNELL, B.M. and LORD, A.R. 1972. Correlation of the Lower Pleistocene Crag at depth in Suffolk. *Geological Magazine*, **109**, 137-139.

BORNEMANN, J.G. 1855. Die mikroskopische Fauna des Septarienthones von Hermsdorf. -bei Berlin. *Zeitschrift für deutsche Geologische Gesellschaft,* Berlin, 7, 307-371.

BOSQUET, P. 1852. Description des Entomostraces fossilie des terrains de la France et de la Belgique. *Mèmoires de l'Académie royal des Sciences, des lettres et des beaux-arts de Belgiques*, Brussels, **24**, 142pp., 6pls.

BOSWELL, P.G.H. 1952. The Pliocene-Pleistocene boundary in the east of England. *Proceedings of the Geologists' Association*, **63**(4), 301-312.

BRADY, G.S. 1865. Deep sea dredging on the coast of Northumberland and Durham in 1864. Report of the 34th *Meeting of the British Association for the Advancement of Science*, Bath September *1864*, London, 189-193.

BRADY, G.S. 1868. A monograph of Recent British Ostracoda. *Transactions of the Linnean Society*, London, **26**(2), 253-495. BRADY, G.S., 1868.

BRADY G.S. 1878. A monograph of the Ostracoda of the Antwerp Crag. *Transactions of the Geological Society of London*, London, **10**, 379-409, pls 62-69.

BRADY, G.S., CROSSKEY, H. and ROBERTSON, D. 1874. A monograph of the Post-Tertiary Entomostracea of Scotland including species from England and Ireland. *Palaeontographical Society (Monograph)*, London, **1874**, 1-232, pls 1-16.

CHARLESWORTH, E. 1835. Observations on the Crag Formation and its organic remains: with a view to establishing a division of the Tertiary strata overlying the London Clay in Suffolk. *Edinburgh and Dublin Philosophical Magazine*, series 3, **7**, 81-94.

CHARLESWORTH, E. 1837. A notice of the remains of vertebrated animals in the Tertiary beds of Norfolk and Suffolk. *Report of the British Association for the Advancement of Science*, **1836**, 84-86.

CRONIN, T.M. 1991. Late Neogene marine Ostracoda from Tjörnes, Iceland. *Journal of Paleontology*, Chicago, **65**(5), 767-789.

DIXON, R.G. 1979. Sedimentary facies in the Red Crag (Lower Pleistocene, East Anglia). *Proceedings of the Geologists' Association*, **90**, 117-132.

DOPPERT, J.W. 1980. Lithostratigraphy and biostratigraphy of marine Neogene deposits in the Netherlands. *Mededelingen van's Rijks geologischen Dienst*, Leiden, **32**(16), 255-311.

FOURNIGUET J., TRAUTMANN, F., MARGEREL, J.P., WHATLEY, R.C., MAYBURY, C.A. and MORZADEC-KERFOURN, M.T. 1989. Les argiles et sables pliocènes de Saint-Jean-la-Poterie (Morbihan): Sédimentologie, micropaléontologie (foraminifères, ostracodes et palynologie). *Géologie de la France*, **1-2**, 55-78, 3pls.

FUNNELL, B.M. 1983. Preliminary note on the Foraminifera and stratigraphy of C.E.G.B. Sizewell borehole L & S. *Bulletin of the Geological Society of Norfolk*, **33**, 54-62.

FUNNELL, B.M. 1987. Late Pliocene and early Pleistocene stages of East Anglia and the adjacent North Sea. *Quaternary Newsletter*, Glasgow, **52**, 1-11.

FUNNELL, B.M. and WEST, R.G. 1977. Preglacial Pleistocene deposits of East Anglia. In: Shotton, F.W. (ed.), British Quaternary Studies: Recent Advances. Oxford University Press, pp. 247-265.

GIBBARD, P.L. and ZALASIEWICZ, J.A. 1988. Pliocene-Middle Pleistocene of East Anglia Field Guide. Quaternary Research Association, Cambridge, 195pp.

HARMER, F.W. 1896. On the Pliocene deposits of Holland and their relationship for the establishment of a new zone, "Amstelian", and some remarks on the geological conditions of the Pliocene Epoch in Northern Europe. *Quarterly Journal of the Geology Society of London*, **52**, 748-782.

HARMER, F.W. 1900a. On a proposed new classification for the Pliocene deposits for the east of England. *Report of the British Association for the Advancement of Science*, London, **1899**, 751-753.

HARMER, F.W. 1900b. The Pliocene deposits of east of England. Part II. The Crag of Essex (Waltonian) and its' relation to that of Suffolk and Norfolk. With a report on the inorganic constituents of the Crag by Joseph Lomas. *Quarterly Journal of the Geological Society of London*, **56**, 705-744.

HARMER, F.W. 1902. A sketch of the later Tertiary history of East Anglia. *Proceedings of the Geologists' Association*, **17**, 416-479.

HARRISON, D.J. 1977. *The ostracod genus Aurila from the Pliocene deposits of Brittany and its European Tertiary distribution with regard to the Messinian salinity crisis.* Unpub. M.Sc. Thesis, University of Wales, 231p.

HAZEL, J.E. 1967. Classification and distribution of the Recent Hemicytheridae and Trachyleberididae (Ostracoda) off northeastern North America. *U.S. Geological Survey Professional Paper*, Washington D.C., **564**, 1-49, 11pls.

HIRSCHMANN, N. 1909. Beitrag zur Kenntnis der Ostracoden fauna des Finnischen Meerbusens. *Meddelangen af Societas pro Fauna et Flora Fennica*, **35**, 282-296.

HORNE, D.J. and KERR, P. 1989. Ostracods and foraminifera from the Pleistocene Knocknasillage Member, County Wexford, Ireland. *Geological Journal*, Liverpool, **24**, 71-74, 2pls.

HORNE, D.J. and WHITTAKER, J.E. 1983. On *Baffinicythere howei* Hazel. *A Stereo-Atlas of Ostracod Shells*, **10**(9), 53-62.

HUNT, C.O. 1989. The palynology and correlation of the Waltonian (Red Crag Formation, Pliocene). *Journal of the Geological Society*, **146**, 743-745.

JONES, T. 1850. Description of the Entomostraca of the Pleistocene beds of Newbury, Copford, Clacton and Grays. *Annals of the Magazine of natural History ser.* 2, **6**, 25-28, pl. 3.

JONES, T. 1857. A monograph on the Tertiary Entomostraca of England. *Palaeontographical Society (Monograph)*, London, **9**, 68pp., 6pls.

JONES, T. 1870. Notes on the Tertiary Entomostraca of England. *Geological Magazine*, London, **7**, 155-159.

JONES, T. and SHERBORN, C. 1887. Further notes on the Tertiary Entomostraca of England with special reference to those from the London Clay. *Geological Magazine*, London, **3**(4-9), 385-393, 450-460, pl. 1.

JONES, T. and SHERBORN, C. 1889. A supplementary monograph on the Tertiary Entomostraca of England. *Palaeontographical Society (Monograph)*, London, **69**, 55pp., 3pls.

KOLLMANN, K. 1960. Cytherideinae und Schulerideinae n. subfam. (Ostracoda) aus dem Neogen des östlichen Österreich. *Mittelrheinischer Geologischer Ges*chichte, Wien, **51**, 89-195.

KUIPER, W.N. 1918. *Oligocäne und Miocäne Ostracoden aus den Nierderlanden.* Proefschr., Univ. Groningen, Groningen (Gebr. Hoitsema), 1-91, 3pls.

LIEBAU, A. 1991. Skulptur-Evolution bei Ostrakoden am Beispiel europäischer "Quadracytheren". *Geologische und Paläontogische*. Westf., Münster, **13**, 3 95pp., pls 1-95.

LORD, A.R., HORNE, D.J., and ROBINSON, J.E. 1988. An introductionary guide to the Neogene and Quaternary of East Anglia for ostracod workers. *British Micropalaeontological Society Field Guide*, **5**, 10pp.

LYELL, C. 1839. On the relative ages of the Tertiary deposits commonly called "Crag" in the counties of Norfolk and Suffolk. *Proceedings of the Geologists' Association*, **3**, 125-130.

MATHERS, S.J. AND ZALASIEWICZ, J.A. 1988. The Red Crag and Norwich Crag Formations of southern East Anglia. *Proceedings of the Geologists' Association*, **99**(4), 261-278.

MAYBURY, C.A. 1985. *Taxonomy, palaeoecology and biostratigraphy of Pliocene benthonic Ostracoda from St. Erth and N.W. France*. Unpub. Ph.D. thesis, University of Wales, 705pp., 49pls.

MAYBURY, C.A. and WHATLEY, R.C. 1986. *Roundstonia magna* Maybury & Whatley *sp. nov. A Stereo-Atlas of Ostracod Shells*, **13**(20), 93-96.

MOYES, J. 1959. Répartition et valeur des *Ostracodes dans l'interprétation du Miocéne nord-Aquitain. Travuaux. Science Centre Géologique*, Bordeaux, thése, 118p, 16pls.

MÜLLER, O.F. 1785. *Entomostraca seu insecta testacea, quae in aquis Daniae et Norvegiae reperit, descripsit et iconibus illustravit*. Leipzig and Copenhagen, 135pp., 21pls.

MÜNSTER, G. von 1830. Über einige fossile Arten *Cypris* (Müller, Lamk.) und *Cythere* (Müller, Latreille, Desmarèest). *Jahrbücher der Mineralogie und Geologie, Petrefakt.*, **1**, 60-67.

NEALE, J.W. 1973. *Roundstonia globulifera* (Brady, 1868) n. gen. (Crust. Ost.) une espèce charactéristique de Pléistocène et (?) de l'actuel. *Revue de Micropaleontologie*, **16**(2), 125-131.

OERTLI, H. and KEIJ, A.J. 1955. Drei neue ostrakoden-arten aus dem Oligozän westeuropas. *Verband Schweizerische Petrol-Geologischen und Ing.*, **22**(62), 19-28.

PRESTWICH, J. 1871. On the structure of the Crag-beds of Suffolk and Norfolk with some observations on the organic remains. Part II. The Red Crag of Essex and Suffolk. *Quaterly Journal of the Geological Society*, London, **27**, 325-356.

REUSS, E. 1850. Die fossilen entomostracen des Oesterreichischen Tertiarbeckens. *Naturwisseneschaftliche Abhandlungen*, Wein, **3**, 41-91.

SPEYER, O. 1863. Die ostracoden aus den kassler Tertiarbilugen. *Bericht des Naturwisseneschaftlichen vereins*, Cassal, 63pp., 4 pls.

SWAIN, F.M. 1968. Ostracoda from the Upper Tertiary Waccamaw Formation of North Carolina and South Carolina. *U.S. Geological Survey, Professional Paper*, **573-D**, 1-37.

TRIEBEL, E. 1950. Homöomorphe ostracoden - Gattungen. *Senckenbergiana*, **31**, 313-330.

UFFENORDE, H. 1981. Ostracoden aus dem Oberoligozän und Miozän des unteren Elbe-Gebietes (Niedersachsen und Hamburg, NW-deutsches Tertiärbecken). *Palaeontographica*, Stuttgart, Abt. **A172**, 103-198, 10pls.

VAN DEN BOLD, W.A. 1957. Oligo-Miocene Ostracoda from southern Trinidad. *Micropaleontology*, **3**(3), 231-254.

WEISS, R.H. 1983. Rasterelektronenmikroskopische untersuchungen an Oligozän marinen ostrakoden. *Palaeontographica Abt.* **A182**, 44-82.

WEST, R.G. 1961. Vegetational history of the Early Pleistocene of the Royal Society Borehole at Ludham, Norfolk. *Philosophical Transactions of the Royal Society of London*, **B155**, 437-453.

WEST, R.G., DEVOY, R.J.N., FUNNELL, B.M. and ROBINSON, J.E. 1984. Pleistocene deposits at Earnley, Bracklesham Bay, Sussex. *Philosophical Transactions of the Royal Society*, London, **B306**, 137-157.

WHATLEY, R.C. 1988. Ostracoda and palaeogeography. In: De Decker, P. Colin, J.P., and Peypouquet, J.P. (eds), *Ostracoda in the Earth Sciences*, 102-124, Elsevier, Amsterdam.

WHATLEY, R.C. and MAYBURY, C.A. 1986. On *Roundstonia minima* Maybury & Whatley sp. nov. *A Stereo-Atlas of Ostracod Shells*, **13**(20), 97-100.

WHATLEY R.C. and MAYBURY, C.A. 1988. On *Loxoconcha pararhomboidea. A Stereo-Atlas of Ostracod Shells*, **15**(1), 9-12.

WILKINSON, I.P. 1980. Coralline Crag Ostracoda and their environmental and stratigraphical significance. *Proceedings of the Geologists' Association*, London, **91**, 291-306.

WOOD, A.M. 1993. *Recent Ostracoda and mid-Pliocene Climatic change*. Unpubl. Ph.D. thesis, University of Wales, 336pp., 45pls.

WOOD, A.M. (in press). A new and inter-regional correlation of the Waltonian (Red Crag Formation, Pliocene), based on ostracod biostratigraphy. *Geologie en Minjbouw*.

WOOD, A.M., WHATLEY, R.C., CRONIN, T.M. and HOLTZ, T. 1994. Pliocene palaeotemperature reconstruction of the southern North Sea based on Ostracoda. *Quaternary Science Reviews*, **12**, 747-767.

WOOD, A.M., WHATLEY, R.C., MAYBURY, C.A. and WILKINSON, I.P. 1992. Three new species of Cytheracean Ostracoda from the Coralline Crag at Orford, Suffolk. *Journal of Micropalaeontology*, **11**, 211-220.

WOOD, A.M. and WHATLEY, R.C. (in press a). The genera *Muellerina* Bassiouni, 1965 and *Thaerocythere* Hazel, 1967 from the Neogene of Northwest Europe. *Journal of Micropalaeontology*.

WOOD, A.M. and WHATLEY, R.C. (in press b). New ostracod based biostratigraphy for the Pliocene marine succession of the Netherlands. *2nd European Ostracologists Meeting*, July, 1993, Glasgow.

WOOD, S.V. snr 1866. On the structure of the Red Crag. *Quarterly Journal of the Geological Society*, London, **22**, 538-552.

WOOD, S.V., snr 1872. Supplement to the Crag Mollusca. Part I (Univalves) with a introduction on the Crag district by Wood, S.V. jun. and Harmer, F.W. *Palaeontographical Society* (*Monograph*), **113**, pp. 25.

WOUTERS, K. 1973. Le genre *Aurila* Pokorný (Crust., Ostr.) dans le Plio-Pliéstocène de Belgique. *Revue de Micropaleontologie*, Paris, **16**(4), 194-201.

WOUTERS, K. 1978. *Een systematische, biostratigrafische en Paleobiologische studie van de Ostracoda uit Miocene Afzettingen in Noord-Belgie*. Unpub. Ph.D. thesis, University of Leuven, 338pp., 48pls.

WOUTERS, K. 1979. On the taxonomy and distribution of some European species of the genus *Muellerina* Bassiouni, 1965. In: Serbian Geological Society (eds), Proceedings of the VII International Symposium on Ostracodes, Belgrade, 1978. *Taxonomy, Biostratigraphy and Distribution of Ostracodes*, Serbian Geological Society, Belgrad. pp.223-232, 2pls.

ZALASIEWICZ, J.A. and MATHERS, S.J. 1985. Lithostratigraphy of the Red Crags of the Aldeburgh-Orford area, south-east Suffolk. *Geological Magazine*, **122**, 287-296.

ZALASIEWICZ, J.A., MATHERS, S.J., HUGHES, M.J. GIBBARD, P.L. *et al.* 1988. Stratigraphy of the Red Crag and the Norwich Crag Formation between Aldeburgh and Sizewell Suffolk, England. *Philospohical Transactions of the Royal Society*, London, **B322**, 11-272.

Plate 1

Aurila sherborni Wood *et al.*, 1992
Fig. 1: ARV-M AMW/PL/W/01, ext. lat. 790 x 450. W1, Red Crag Fm., Naze Cliff, Walton-on-the-Naze.

Aurila strongyla Wouters, 1973
Fig. 2: ALV-F AMW/PL/W/02, ext. lat. 660 x 490. W1, Red Crag Fm., Naze Cliff, Walton-on-the-Naze.
Fig. 3: Acp-M (RV) AMW/PL/W/03, ext. lat. 660 x 440. W1, Red Crag Fm., Naze Cliff, Walton-on-the-Naze.

Aurila trigonula (Jones, 1857)
Fig. 4: ALV-F AMW/PL/W/04, ext. lat. 650 x 450. W1, Red Crag Fm., Naze Cliff, Walton-on-the-Naze.

Muellerina lacunosa (Jones, 1857)
Fig. 5: ARV-F AMW/PL/W/05, ext. lat. 770 x 390. W1, Red Crag Fm., Naze Cliff, Walton-on-the-Naze.

Muellerina metabyssicola Wood & Whatley, in press
Fig. 6: ARV-M AMW/PL/W/06, ext. lat. 620 x 320. W1, Red Crag Fm., Naze Cliff, Walton-on-the-Naze.

Muellerina pliocenica Wood & Whatley, in press
Fig. 7: ARV-M AMW/PL/W/07, ext. lat. 660 x 290. W1, Red Crag Fm., Naze Cliff, Walton-on-the-Naze.

Triginglymus sp. cf. *Cythere petrosa* Brady, 1878
Fig. 8: ARV-F AMW/PL/W/08, ext. lat. 800 x 430. W1, Red Crag Fm., Naze Cliff, Walton-on-the-Naze.
Fig. 9:ARV-M AMW/PL/W/09, ext. lat. 820 x 400. W1, Red Crag Fm., Naze Cliff, Walton-on-the-Naze.

Thaerocythere ?oedichilus (Brady, 1878)
Fig. 10: ALV-F AMW/PL/W/10, ext. lat. 840 x 480. W1, Red Crag Fm., Naze Cliff, Walton-on-the-Naze.

Thaerocythere trachypora (Jones, 1857)
Fig. 11: ALV-F AMW/PL/W/11, ext. lat. 700 x 410. W1, Red Crag Fm., Naze Cliff, Walton-on-the-Naze.

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Plate 2

Thaerocythere trachypora (Jones, 1857)
Fig. 1: ACp (RV) AMW/PL/12 ext. lat. 730 x 390. W2, Red Crag Fm., Naze Cliff, Walton-on-the-Naze.

Thaerocythere wittei Wood & Whatley, in press
Fig. 2: ALV-F AMW/PL/W/13 ext. lat. 650 x 390. W2, Red Crag Fm., Naze Cliff, Walton-on-the-Naze.

Thaerocythere epistylium sp. nov.
Fig. 3: Holotype ARV OS 14856 ext. lat. 780 x 380. S4, Coralline Crag Fm., Sutton Knoll.
Fig. 4: Paratype ARV-F OS 14857 ext. lat. 700 x 380. S3, Coralline Crag Fm., Sutton Knoll.

Leptocythere recurata (Jones & Sherborn, 1887)
Fig. 5: ACp (RV) AMW/PL/W/14 ext. lat. 570 x 290. W1, Red Crag Fm., Naze Cliff, Walton-on-the-Naze.

Cytheridea sp. cf. C. *mülleri mülleri* (v. Münster, 1830)
Fig. 6: ALV AMW/PL/W/15 ext. lat. 870 x 440. W1, Red Crag Fm., Naze Cliff, Walton-on-the-Naze.
Fig. 7: ARV AMW/PL/W/16 ext. lat. 840 x 410. W1, Red Crag Fm., Naze Cliff, Walton-on-the-Naze.
Fig. 8: ALV AMW/PL/W/17 ext. lat. 870 x 440. W1, Red Crag Fm., Naze Cliff, Walton-on-the-Naze.

Cytheridea sp. A
Fig. 9: ALV-F AMW/PL/W/18 ext. lat. 810 x 470. W1, Red Crag Fm., Naze Cliff, Walton-on-the-Naze.

Cyprideis sp.
Fig. 10: ARV-?F AMW/PL/W/19 ext. lat. 1040 x 600. W1, Red Crag Fm., Naze Cliff, Walton-on-the-Naze.

Haplocytheridea pinguis (Jones, 1857)
Fig. 11: LVA-2 AMW/PL/W/20 ext. lat. 720 x 380. W1, Red Crag Fm., Naze Cliff, Walton-on-the-Naze.

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Plate 3

Haplocytheridea robusta Wood *et al.*, 1992
Fig. 1: LVA-1 AMW/PL/W/20 ext. lat. 845 x 480. W2, Red Crag Fm., Naze Cliff, Walton-on-the-Naze.

Haplocytheridea sp. aff. *H. cypridoides* (Brady, 1878)
Fig. 2: ALV AMW/PL/W/21 ext. lat. 910 x 450. W2, Red Crag Fm., Naze Cliff, Walton-on-the-Naze.

Cytheromorpha sp. A
Fig. 3: ARV-M AMW/PL/W/22 ext. lat. 530 x 280. W1, Red Crag Fm., Naze Cliff, Walton-on-the-Naze.
Fig. 4: ARV-M AMW/PL/W/22 int. lat. 530 x 280. W1, Red Crag Fm., Naze Cliff, Walton-on-the-Naze.

Pontocythere botellina (Jones, 1870)
Fig. 5: ARV-F AMW/PL/W/23 ext. lat. 860 x 380. W1, Red Crag Fm., Naze Cliff, Walton-on-the-Naze.
Fig. 6: ARV-F AMW/PL/W/23 int. lat. 860 x 380. W1, Red Crag Fm., Naze Cliff, Walton-on-the-Naze.

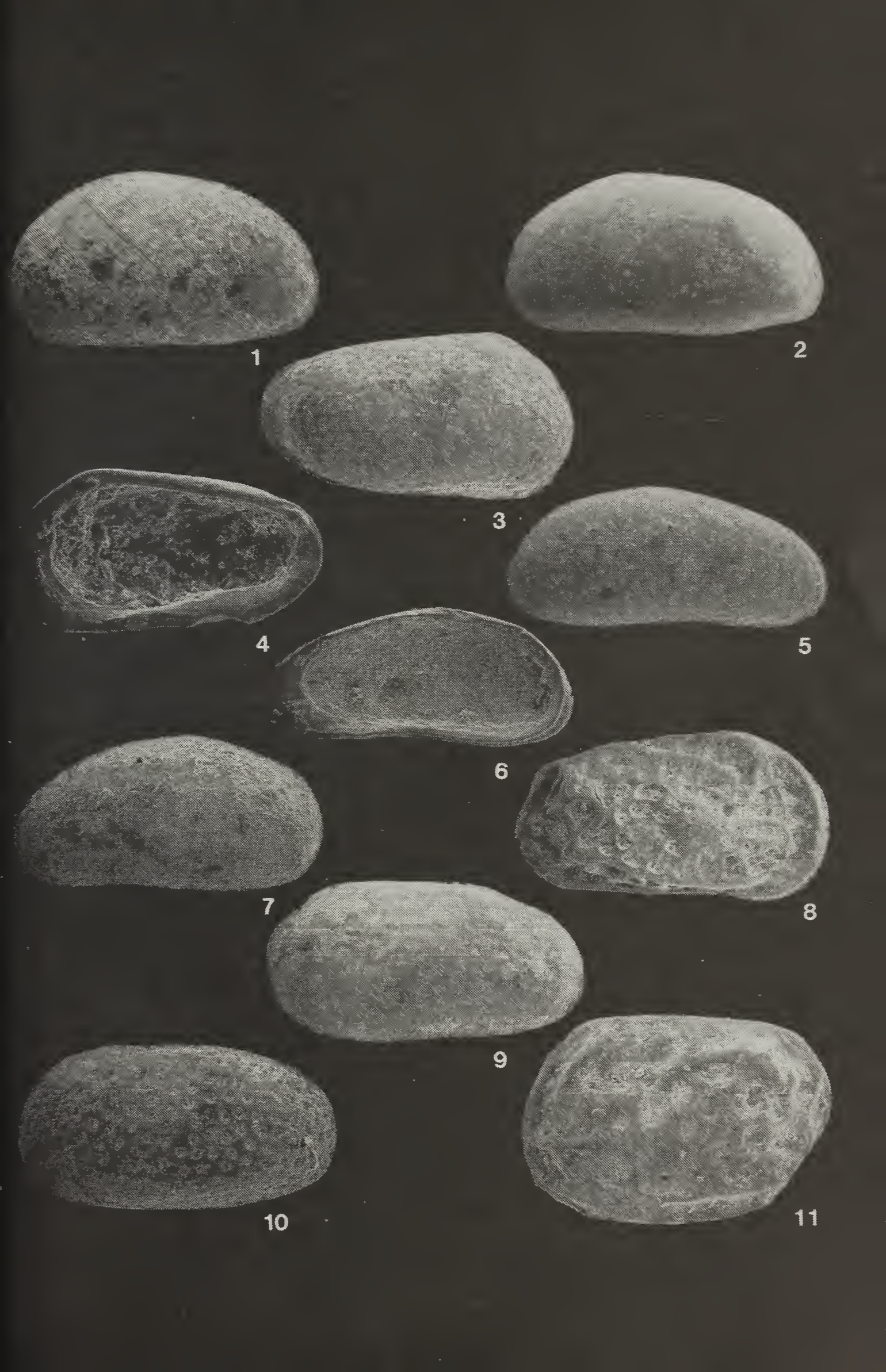
Pontocythere sp. cf. *P. elongata* (Brady, 1868)
Fig. 7: LVA-1/2 AMW/PL/W/24 ext. lat. 780 x 400. W3, Red Crag Fm., Naze Cliff, Walton-on-the-Naze.

Cletocythereis jonesi Wood *et al.*, 1992
Fig. 8: ARV-F AMW/PL/W/25 ext. lat. 980 x 510. W1, Red Crag Fm., Naze Cliff, Walton-on-the-Naze.

Cytheretta harmeri Wilkinson, 1980
Fig. 9: ARV-M AMW/PL/W/26 ext. lat. 920 x 460. W1, Red Crag Fm., Naze Cliff, Walton-on-the-Naze.

Cytheretta woodiana (Jones, 1857)
Fig. 10: LVA-2 AMW/PL/W/27 ext. lat. 890 x 460. W1, Red Crag Fm., Naze Cliff, Walton-on-the-Naze.

Schizocythere pliocenica Wilkinson, 1980
Fig. 11: ALV-M AMW/PL/W/28 ext. lat. 510 x 340. W1, Red Crag Fm., Naze Cliff, Walton-on-the-Naze.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The Geological Society of Norfolk exists to promote the study and understanding of geology, particularly in East Anglia, and holds monthly meetings throughout the year.

Visitors are welcome to attend meetings and may apply for membership of the society. For further details write to The Secretary, Geological Society of Norfolk, Castle Museum, Norwich NR1 3JU.

Copies of the Bulletin may be obtained from the Secretary at the address given above; it is issued free to members.

The illustration on the front cover is figure 3 from the article by Wood which makes up this issue of the Bulletin. It shows a reconstruction of the Neogene ostracod *Schizocythere pliocenica* Wilkinson, 1980. The scale bar A = 100μm.

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